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Buckling of a Column With Non-Linear Lateral Supports

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Introduction

During the investigation of the buckling phenomenon of thin spherical shells[1] and thin cylindrical shells,[2] it was found that for these structures the load sustained is not a linear function of the deflection even when the stresses are below the elastic limit and are proportional to the corresponding strains. This non-linear load *vs.* deflection relation gives a buckling phenomenon entirely different from that of the classical theory. However, the exact solution of these problems involves a pair of non-linear partial differential equations. It is difficult to obtain an exact solution. The method adopted in these investigations is the so-called energy method, where a plausible form of deflection of the shell is assumed, first with certain undetermined parameters, and then these parameters are determined by the condition that the first variation of the strain energy of the system must be zero. Although this method yields quite satisfactory results for the cases investigated, it is felt that due to the novel nature of the problem, an exact solution is very desirable. Experiments on a column with non-linear lateral supports[3] show that the essential characteristics of the buckling of curved shells can be reproduced by this structure. The problem of a column with non-linear lateral supports is, however, much simpler than the problem of curved shells, and an exact solution can be obtained without any mathematical difficulty. In the present paper, an exact solution of the column problem will be carried out.

During his investigation on the buckling of thin curved plates, Cox[4] has used the same analogy to demonstrate the non-linear character of the buckling phenomenon, and has also carried out the mathematical analysis of a column supported by two rods pin-jointed to the center of the column. However, Cox's calculation seems unnecessarily complicated. The method developed in this paper is believed to be more general, because it can be applied to supports with arbitrary elastic properties.

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General Theory for Straight Columns

Using the variational method for the calculation of the equilibrium positions of the column, let the column be initially straight and its center line be taken as the x-axis. (Fig. 1.) The lower end of the column is taken as the origin. The column is supported laterally at g-points $x_1, x_2, \ldots, x_g$ by springs of non-linear load *vs.* deflection characteristics. The springs are assumed to be unloaded when the column is straight. Denote the deflections of the springs by $\delta_1, \delta_2, \ldots, \delta_g$. Then the forces given by the springs when they are deflected can be expressed as $F_1(\delta_1), F_2(\delta_2), \ldots, F_g(\delta_g)$. The elastic energy S stored in these springs at the deflections $\delta_1, \delta_2, \ldots, \delta_g$ can be easily calculated as

$$S_1(\delta_1) = \int_0^{\delta_1} F_1(\xi)d\xi$$

$$S_2(\delta_2) = \int_0^{\delta_2} F_2(\xi)d\xi$$

or

$$S_g(\delta_g) = \int_0^{\delta_g} F_g(\xi)d\xi \qquad (1)$$

Let the deflection of the column normal to x-axis be denoted by $w(x)$. Then

$$\delta_1 = w(x_1)$$
$$\delta_2 = w(x_2)$$

or

$$\delta_g = w(x_g) \qquad (2)$$

If it is assumed that the column is simply supported at

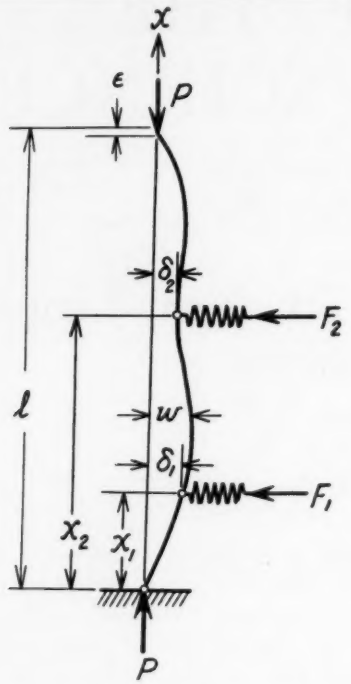

FIG. 1. Column with lateral supports.

the two ends, $w(x)$ can be expanded into a Fourier series such that

$$w(x) = \sum_{n=1}^{\infty} a_n \sin (n\pi x/l) \tag{3}$$

where l is the length of the column. Denoting the Young's modulus by $\mathbf{E}$ and the moment of inertia of the column section by $\mathbf{I}$, the bending elastic energy involved in the deflection $w(x)$ is

$$W_1 = \frac{\mathbf{EI}}{2}\int_0^l \left(\frac{d^2w}{dx^2}\right)^2 dx = \frac{\mathbf{EI}l}{4}\sum_{n=1}^{\infty}\left(\frac{n\pi}{l}\right)^4 a_n^2 \tag{4}$$

The elastic energy stored in the springs can be calculated by means of Eq. (1).

$$W_2 = \sum_{m=1}^{g} S_m(\delta_m) = \sum_{m=1}^{g}\int_0^{\delta_m} F_m(\xi)d\xi \tag{5}$$

The lowering of potential of the compression force P applied at the ends of the column due to the deflection $w(x)$ is

$$W_3 = -\frac{P}{2}\int_0^l \left(\frac{dw}{dx}\right)^2 dx = -\frac{Pl}{4}\sum_{n=1}^{\infty}\left(\frac{n\pi}{l}\right)^2 a_n^2 \tag{6}$$

The conditions of equilibrium can be found by putting the first variation of the sum of W_1, W_2, W_3 with respect to a_n equal to zero. Thus

$$\frac{\mathbf{EI}l}{2}\left(\frac{n\pi}{l}\right)^4 a_n + \sum_{m=1}^{g} F_m(\delta_m)\frac{\partial\delta_m}{\partial a_n} - \frac{Pl}{2}\left(\frac{n\pi}{l}\right)^2 a_n = 0 \tag{7}$$

By means of Eqs. (2) and (3)

$$(\partial\delta_m/\partial a_n) = \sin (n\pi x_m/l) \tag{8}$$

Therefore by substituting this value of $\partial\delta_m/\partial a_n$ into Eq. (7), the following equation is obtained for the coefficients a_n,

$$a_n = \frac{\sum_{m=1}^{g} \sin (n\pi x_m/l)\cdot F_m(\delta_m)}{\frac{Pl}{2}\left(\frac{n\pi}{l}\right)^2 - \frac{\mathbf{EI}l}{2}\left(\frac{n\pi}{l}\right)^4} \tag{9}$$

By introducing the Euler column load $P_{\mathbf{E}} = \dfrac{\mathbf{EI}\pi^2}{l^2}$, Eq. (9) can be rewritten in the following form

$$\frac{a_n}{l} = \frac{2}{\pi^2}\frac{\sum_{m=1}^{g} \sin\dfrac{n\pi x_m}{l}\cdot\dfrac{F_m(\delta_m)}{P_{\mathbf{E}}}}{n^2\left[\dfrac{P}{P_{\mathbf{E}}} - n^2\right]} \tag{10}$$

This equation allows one to calculate the coefficients a_n if the forces $F_1, F_2, \ldots, F_g$ acting on the column are known. The known relations are the functions $F_1(\delta_1)$, $F_2(\delta_2), \ldots, F_g(\delta_g)$, *i.e.*, the spring forces as functions of their respective deflections. However, by using Eqs. (2) and (3), the following is obtained

$$(\delta_s/l) = \sum_{n=1}^{\infty} (a_n/l) \sin (n\pi x_s/l) \tag{11}$$

By substituting Eq. (10) into Eq. (11)

$$\frac{\delta_s}{l} = \frac{2}{\pi^2}\sum_{m=1}^{g}\frac{F_m(\delta_m)}{P_{\mathbf{E}}}\sum_{n=1}^{\infty}\frac{\sin\dfrac{n\pi x_m}{l}\cdot\sin\dfrac{n\pi x_s}{l}}{n^2\left[\dfrac{P}{P_{\mathbf{E}}} - n^2\right]}, \quad (s = 1, 2, \ldots g) \tag{12}$$

If

$$K_{sm} = \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{\sin\dfrac{n\pi x_m}{l}\sin\dfrac{n\pi x_s}{l}}{n^2\left[\dfrac{P}{P_{\mathbf{E}}} - n^2\right]} \tag{13}$$

Eq. (12) can be rewritten in the form

$$(\delta_s/l) = \sum_{m=1}^{g} K_{sm}(F_m/P_{\mathbf{E}}), \ (s = 1, 2, \ldots g) \tag{14}$$

With a given value of $P/P_{\mathbf{E}}$, the coefficients K_{sm} can be calculated. These coefficients are symmetrical, *i.e.*,

$$K_{sm} = K_{ms} \tag{15}$$

which can be easily seen from Eq. (13). When these coefficients are calculated, Eq. (14) consists of a system of g equations for the g unknowns, $\delta_1, \delta_2, \ldots, \delta_g$. Therefore the values of these deflections can be found. Then the spring forces $F_1, F_2, \ldots, F_g$ can be calculated. The Fourier coefficients a_n/l can then be determined by means of Eq. (10). The problem is thus completely solved.

The merit of the present method is that the fundamental parameters K_{sm} are independent of the charac-

teristics of the supporting springs. And therefore they are applicable to a wide class of problems.

Case of Two Equally Spaced Supports

For the case of two equally spaced supports, the coefficients K_{sm} can be immediately calculated as

$$K_{11} = \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{\sin^2\frac{n\pi}{3}}{n^2\left[\frac{P}{P_E}-n^2\right]}$$

$$K_{12} = K_{21} = \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{\sin\frac{n\pi}{3}\sin\frac{2n\pi}{3}}{n^2\left[\frac{P}{P_E}-n^2\right]}$$

$$K_{22} = \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{\sin^2\frac{2n\pi}{3}}{n^2\left[\frac{P}{P_E}-n^2\right]} \qquad (16)$$

These series can be easily summed by well-known relations as

$$K_{11} = K_{22} = \left[\frac{2}{9}+\frac{1}{4\theta}\left\{3\cot\theta-\cot\frac{\theta}{3}\right\}\right]\Big/\frac{P}{P_E}$$

$$K_{12} = K_{21} = \left[\frac{1}{9}-\frac{1}{4\theta}\left\{3\csc\theta-\csc\frac{\theta}{3}\right\}\right]\Big/\frac{P}{P_E} \qquad (17)$$

where

$$\theta = \pi\sqrt{P/P_E} \qquad (18)$$

If the two spring supports have the same characteristics, and the deflection of the column is symmetrical, *i.e.*, $\delta_1 = \delta_2 = \delta$, then $F_1 = F_2 = F$. Eq. (14) can be simplified into

$$(\delta/l) = (K_{11}+K_{22})(F/P_E) \qquad (19)$$

$K_{11} + K_{12}$ can be obtained from Eq. (17), and written in the following form:

$$K_{11}+K_{12} = \left[\frac{1}{3}-\frac{1}{4\theta}\left\{3\tan\frac{\theta}{2}-\tan\frac{\theta}{6}\right\}\right]\Big/\frac{P}{P_E} \qquad (20)$$

For the degenerate case of springs with linear characteristics, *i.e.*,

$$F/P_E = \alpha\cdot(\delta/l) \qquad (21)$$

from Eqs. (19) and (20) the following relation for symmetrical buckling is derived:

$$\alpha = \frac{P_1/P_E}{\frac{1}{3}-\frac{1}{4\theta}\left\{3\tan\frac{\theta}{2}-\tan\frac{\theta}{6}\right\}} \qquad (22)$$

Eq. (22) can be also written in the form

$$\alpha = \frac{3(P_1/P_E)\theta}{\theta-3\left\{\sin^2\frac{\theta}{3}\tan\frac{\theta}{2}+\sin\frac{\theta}{3}\cos\frac{\theta}{3}\right\}} \qquad (23)$$

In case of anti-symmetric buckling with linear spring characteristics, $\delta_1 = -\delta_2$, and from Eq. (14)

$$(\delta_1/l) = K_{11}\alpha(\delta_1/l) - K_{12}\alpha(\delta_1/l) \qquad (24)$$

Using the value of K_{11} and K_{12} from Eq. (17)

$$\alpha = \frac{9(P_2/P_E)\theta}{\theta-9\left\{\cot\frac{\theta}{3}+\cot\frac{\theta}{6}\right\}} \qquad (25)$$

Both Eqs. (23) and (25) check the calculations of Klemperer and Gibbons[5] which are limited to linear spring characteristics.

By means of Eq. (10), the shortening ϵ_1 of the column due to bending is

$$\frac{\epsilon_1}{l} = \frac{\pi^2}{4}\sum_{n=1}^{\infty}n^2\left(\frac{a_n}{l}\right)^2 = C_{11}\left(\frac{F_1}{P_E}\right)^2 + C_{12}\frac{F_1F_2}{P_E{}^2} + C_{22}\left(\frac{F_2}{P_E}\right)^2 \qquad (26)$$

The coefficients C_{11}, C_{12}, and C_{22} are functions of P/P_E and are first obtained from Eq. (10) as the following series

$$C_{11} = \frac{1}{\pi^2}\sum_{n=1}^{\infty}\frac{\sin^2\frac{n\pi}{3}}{n^2\left[\frac{P}{P_E}-n^2\right]^2}$$

$$C_{12} = \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{\sin\frac{n\pi}{3}\sin\frac{2n\pi}{3}}{n^2\left[\frac{P}{P_E}-n^2\right]^2}$$

$$C_{22} = \frac{1}{\pi^2}\sum_{n=1}^{\infty}\frac{\sin^2\frac{2n\pi}{3}}{n^2\left[\frac{P}{P_E}-n^2\right]^2} \qquad (27)$$

These series can be summed and give the following expressions for the coefficients

$$C_{11} = C_{22} = \left\{\frac{5}{18}+\frac{3}{16}\left(\cot^2\theta-\frac{1}{9}\cot^2\frac{\theta}{3}\right)+\frac{9}{16\theta}\left(\cot\theta-\frac{1}{3}\cot\frac{\theta}{3}\right)\right\}\Big/\left(\frac{P}{P_E}\right)^2$$

$$C_{12} = \left\{\frac{1}{9}-\frac{3}{8}\left(\frac{\cot\theta}{\sin\theta}-\frac{1}{9}\frac{\cot\frac{\theta}{3}}{\sin\frac{\theta}{3}}\right)-\frac{3}{8\theta}\left(\frac{3}{\sin\theta}-\frac{1}{\sin\frac{\theta}{3}}\right)\right\}\Big/\left(\frac{P}{P_E}\right)^2 \qquad (28)$$

If the springs have same elastic properties and the deflection of the column is symmetrical, *i.e.*, $F_1 = F_2 = F$, Eq. (26) reduces to

$$(\epsilon_1/l) = (C_{11}+C_{12}+C_{22})\left(\frac{F}{P_E}\right)^2 \qquad (29)$$

where

$$C_{11} + C_{12} + C_{22} = \left\{\frac{1}{2} + \frac{3}{16}\left(\tan^2\frac{\Theta}{2} - \frac{1}{9}\tan^2\frac{\Theta}{6}\right) - \frac{9}{8\Theta}\left(\tan\frac{\Theta}{2} - \frac{1}{3}\tan\frac{\Theta}{6}\right)\right\} \Big/ \left(\frac{P}{P_E}\right)^2 \quad (30)$$

The shortening of the column due to direct compression can be expressed as

$$(\epsilon_2/l) = (P/A_E) = (\pi i/l)^2(P/P_E) \quad (31)$$

where A is the cross-sectional area of the column and $i^2 = (I/A)$, i being the radius of gyration of the column section. Therefore, the total shortening of the column is

$$\epsilon/l = (\epsilon_1/l) + (\epsilon_2/l) \quad (32)$$

The bending strain energy can be obtained by substituting the value of a_n from Eq. (10) into Eq. (4), thus

$$\frac{W_1}{P_E l} = B_{11}\left(\frac{F_1}{P_E}\right)^2 + B_{12}\frac{F_1F_2}{P_E{}^2} + B_{22}\left(\frac{F_2}{P_E}\right)^2 \quad (33)$$

The coefficients are functions of P/P_E and can be expressed as the following series:

$$B_{11} = \frac{1}{\pi^2}\sum_{n=1}^{\infty}\frac{\sin^2(n\pi/3)}{[(P/P_E) - n^2]^2}$$

$$B_{12} = \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{\sin(n\pi/3)\sin(2n\pi/3)}{[(P/P_E) - n^2]^2}$$

$$B_{22} = \frac{1}{\pi^2}\sum_{n=1}^{\infty}\frac{\sin^2(2n\pi/3)}{[(P/P_E) - n^2]^2} \quad (34)$$

These series can be summed into the following expressions

$$B_{11} = B_{22} = \left[\frac{1}{6} + \frac{3}{16}\left(\cot^2\Theta - \frac{1}{9}\cot^2\frac{\Theta}{3}\right) + \frac{3}{16\Theta}\left(\cot\Theta - \frac{1}{3}\cot\frac{\Theta}{3}\right)\right] \Big/ \left(\frac{P}{P_E}\right)$$

$$B_{12} = -\left[\frac{3}{16}\left(\frac{\cot\Theta}{\sin\Theta} - \frac{1}{9}\frac{\cot\frac{\Theta}{3}}{\sin\frac{\Theta}{3}}\right) + \frac{3}{16\Theta}\left(\frac{1}{\sin\Theta} - \frac{1}{3\sin\frac{\Theta}{3}}\right)\right] \Big/ \left(\frac{P}{P_E}\right) \quad (35)$$

If the buckling is symmetrical and springs of same properties are used, then Eq. (33) can be again reduced to

$$W_1/P_E l = (B_{11} + B_{12} + B_{22})(F/P_E)^2 \quad (36)$$

where

$$B_{11} + B_{12} + B_{22} = \frac{3}{16}\left\{\left(\sec^2\frac{\Theta}{2} - \frac{1}{9}\sec^2\frac{\Theta}{6}\right) - \frac{2}{\Theta}\left(\tan\frac{\Theta}{2} - \frac{1}{3}\tan\frac{\Theta}{6}\right)\right\} \Big/ \left(\frac{P}{P_E}\right) \quad (37)$$

The strain energy due to the direct compression stress is evidently

$$W_4/P_E l = P\epsilon_2/2P_E l \quad (38)$$

Or by means of Eq. (31),

$$\frac{W_4}{P_E l} = \frac{1}{2}\left(\frac{P}{P_E}\right)^2\frac{P_E}{AE} = \frac{1}{2}\left(\frac{\pi i}{l}\right)^2\left(\frac{P}{P_E}\right)^2 \quad (39)$$

The strain energy stored in the springs is given by Eq. (5). The total strain energy of the system is then given by

$$W/P_E l = (W_1 + W_2 + W_4)/P_E l \quad (40)$$

Different expressions for calculating the equilibrium positions, shortening of column and strain energies have been developed without any assumption as to the function $F(\delta)$. The elastic characteristics of a curved shell are found to correspond to a spring having the load-deflection relation shown in Fig. 2. This

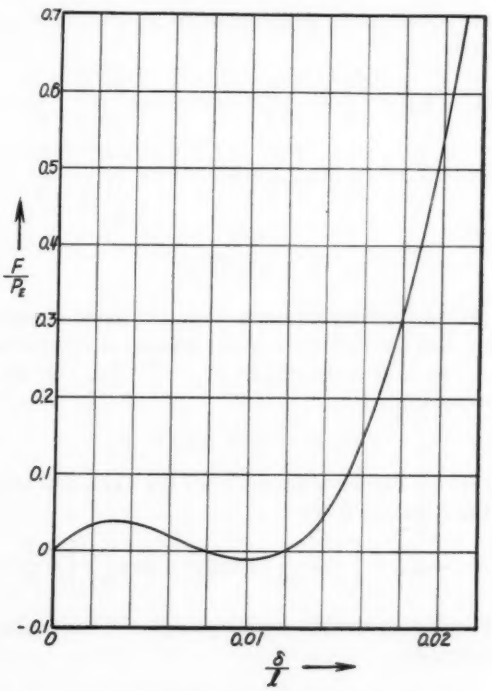

FIG. 2. Non-linear relation between load F and deflection δ of the lateral supporting spring.

particular spring characteristic can be very well represented by the expression

$$F/P_E = a(\delta/l) + b(\delta/l)^2 + c(\delta/l)^3 \quad (41)$$

where a, b, c are constants. These constants can be determined by the initial slope, and the positions of the maximum and minimum of the F *vs.* δ curve.

For the case of symmetrical buckling with identical supporting springs, Eq. (19) can be combined with

Eq. (41) and the following equation for determining δ with a given value of P/P_E obtained.

$$\frac{\delta}{l} = (K_{11} + K_{12}) \left\{ a\left(\frac{\delta}{l}\right) + b\left(\frac{\delta}{l}\right)^2 + c\left(\frac{\delta}{l}\right)^3 \right\} \quad (42)$$

A simple solution of this equation is

$$\delta/l = 0 \quad (43)$$

which represents the unbuckled straight column. Other solutions are given by

$$1 = (K_{11} + K_{12}) \left\{ a + b\left(\frac{\delta}{l}\right) + c\left(\frac{\delta}{l}\right)^2 \right\} \quad (44)$$

which is a quadratic equation for (δ/l), and can be easily solved. After the deflections δ of springs are obtained, other quantities can be calculated without difficulty by means of formulas already given.

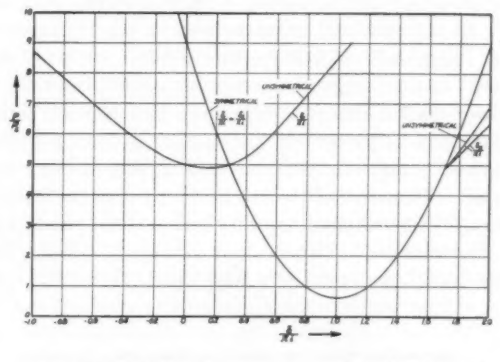

FIG. 3. Relation between the end load P on the column and the deflections δ_1, δ_2 of the two equally spaced lateral supports.

For the unsymmetrical case, it is assumed that the support springs have the same elastic properties, *i.e.*, the values of the constants a, b, c are the same for both springs. Then the combination of Eqs. (18) and (41) gives

$$\frac{\delta_1}{l} = K_{11} \left\{ a\left(\frac{\delta_1}{l}\right) + b\left(\frac{\delta_1}{l}\right)^2 + c\left(\frac{\delta_1}{l}\right)^3 \right\} + K_{12} \left\{ a\left(\frac{\delta_2}{l}\right) + b\left(\frac{\delta_2}{l}\right)^2 + c\left(\frac{\delta_2}{l}\right)^3 \right\}$$

$$\frac{\delta_2}{l} = K_{21} \left\{ a\left(\frac{\delta_1}{l}\right) + b\left(\frac{\delta_1}{l}\right)^2 + c\left(\frac{\delta_1}{l}\right)^3 \right\} + K_{22} \left\{ a\left(\frac{\delta_2}{l}\right) + b\left(\frac{\delta_2}{l}\right)^2 + c\left(\frac{\delta_2}{l}\right)^3 \right\} \quad (45)$$

In trying to solve this system of equations by eliminating one variable, say δ_2, an algebraic equation of the 9th order is obtained for δ_1/l. Since already three possible solutions have been obtained by means of Eq. (42), only six more new solutions are possible. Thus we are faced with the task of deriving a 9th-order equation to obtain six new solutions. However, this lengthy calculation is unnecessary as can be seen in the following process.

By adding and subtracting the two equations in Eq. (45),

$$\frac{\delta_1}{l} + \frac{\delta_2}{l} = (K_{11} + K_{12}) \left[a\left(\frac{\delta_1}{l} + \frac{\delta_2}{l}\right) + b\left(\frac{\delta_1^2}{l^2} + \frac{\delta_2^2}{l^2}\right) + c\left(\frac{\delta_1^3}{l^3} + \frac{\delta_2^3}{l^3}\right) \right]$$

$$\frac{\delta_1}{l} - \frac{\delta_2}{l} = (K_{11} - K_{12}) \left[a\left(\frac{\delta_1}{l} - \frac{\delta_2}{l}\right) + b\left(\frac{\delta_1^2}{l^2} - \frac{\delta_2^2}{l^2}\right) + c\left(\frac{\delta_1^3}{l^3} - \frac{\delta_2^3}{l^3}\right) \right] \quad (46)$$

Putting

$$(\delta_1/l) + (\delta_2/l) = \xi_1 \qquad (\delta_1/l) - (\delta_2/l) = \eta \quad (47)$$

from Eq. (46)

$$\xi = (K_{11} + K_{12}) \left[a\xi + \frac{b}{2}(\xi^2 + \eta^2) + \frac{c}{4}(\xi^3 + 3\xi\eta^2) \right]$$

$$1 = (K_{11} - K_{12}) \left[a + b\xi + \frac{c}{4}(3\xi^2 + \eta^2) \right] \quad (48)$$

The second equation of Eq. (48) has already the root $\eta = 0$ eliminated, since it is contained in Eq. (42). By eliminating η^2, the following cubic equation is obtained for ξ,

$$0 = \xi^3 + 2\frac{b}{c}\xi^2 + \left\{ \frac{ac + b^2}{c^2} - \frac{1}{2c} \times \left(\frac{3}{K_{11} - K_{12}} - \frac{1}{K_{11} + K_{12}} \right) \right\} \xi + \frac{b}{c^2}\left(a - \frac{1}{K_{11} - K_{12}} \right) \quad (49)$$

With a given value of P, this equation can be solved for ξ, and then η can be found from the second equation of Eq. (48). With these values of ξ and η, the values of δ_1/l and δ_2/l can be calculated by means of Eq. (47). With each value of ξ, there are two equal and opposite values of η, which correspond to an interchange of the values of δ_1 and δ_2. The shape of the column is not affected by this interchange and therefore η can be taken as always positive.

As a particular example,

$$a = 2F,\ b = -5640,\ c = 282{,}000 \quad (50)$$

The corresponding relation between the spring force and the spring deflection is shown in Fig. 2. The initial slope of the load *vs.* deflection curve for the spring is so chosen in this particular case that the starting point of buckling occurs at a load $P = 9P_E$.

With these spring characteristics the equilibrium position is first calculated. The results are shown in Fig. 3 where the load P/P_E on the column is plotted against the deflection $\delta/\pi i$. Taking the slenderness ratio of the column to be

$$\pi i/l = 1/100 \quad (51)$$

Therefore the value $\delta/\pi i = 1.00$ corresponds to $\delta/l = 0.010$. Fig. 3 shows clearly the decrease in the load P

with increase in deflection δ once the column starts to buckle. However, a minimum is soon reached and the load increases again at very large values of the deflection δ.

However, in a testing machine the operator cannot control spring deflections δ_1 and δ_2 directly. On the other hand, he can increase or decrease the distance between the end plates of the testing machine. The distance between the end plates determines the end shortening ϵ of the column. Therefore, a better representation of the result of calculation is a diagram of the load plotted against the shortening ϵ. The shortening ϵ can be calculated from Eqs. (26), (28), (29), (30) and (31). The result is shown in Fig. 4. If the column keeps its straight form until the branch point of the solution for symmetrical equilibrium position is reached, it will be impossible to reach the equilibrium positions represented by the curve *A-B-C* in Fig. 4 in the loading process. This is the consequence of the fact that the corresponding end shortening ϵ for this part of the curve is smaller than the end shortening at the branch point. In the loading process, the shortening is always increased by diminishing the distance between the end plates of the testing machine. The actual behavior of the test specimen is probably a sudden jump from the point *A* to the point *C* (Fig. 4) with evident release of elastic energy. If the end plates of the testing machine are brought closer together, the load *P* will gradually increase and follow the curve *C-D* (Fig. 4). The equilibrium positions represented by the portion of the curve *B-C* can be reached by "unloading" the specimen after the buckling, *i.e.*, by moving the end plates of the testing machine apart after it has reached the equilibrium position *C*. However, it is difficult to see how the equilibrium positions represented by the portion of curve *A-B* can be reached.

The three wave buckling of the column with the springs undeformed is indicated by the horizontal line labeled "Euler" in Fig. 4. The unsymmetrical type of buckling gives a load *vs.* shortening relation quite similar to that of symmetrical type.

Under a given value of end shortening which is the geometrical restraint to which the specimen must conform, the condition for the most probable equilibrium state under actual testing circumstances is the minimum elastic energy stored in the system. This statement is based upon the assumption that even if the equilibrium state involving higher elastic energy is stable with respect to infinitesimal disturbances, a disturbance of finite magnitude will help the column to pass the "hump" in the energy and jump to an equilibrium state of lower elastic energy. When a series of such finite disturbances is present in the testing procedure, then the lowest energy state will be certainly the most probable one. Therefore, it is necessary to plot the elastic energy *W* for different equilibrium states against the end shortening ϵ. This is done in Fig. 5. Using the above mentioned criterion, the most probable equi-

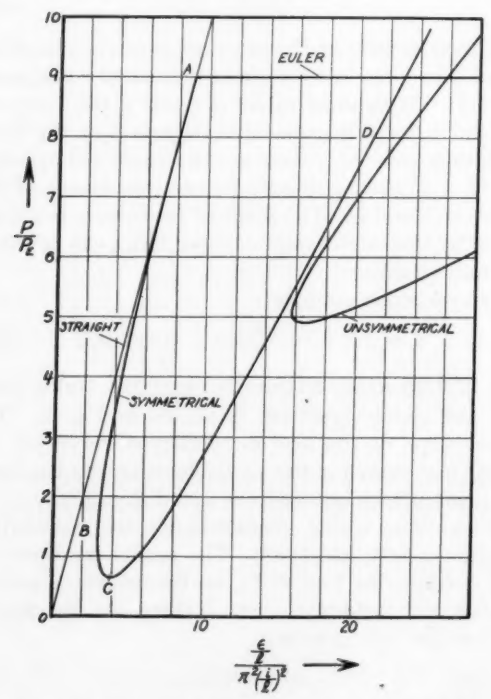

FIG. 4. Relation between the end load *P* on the column with two equally spaced lateral supports and its end shortening ϵ.

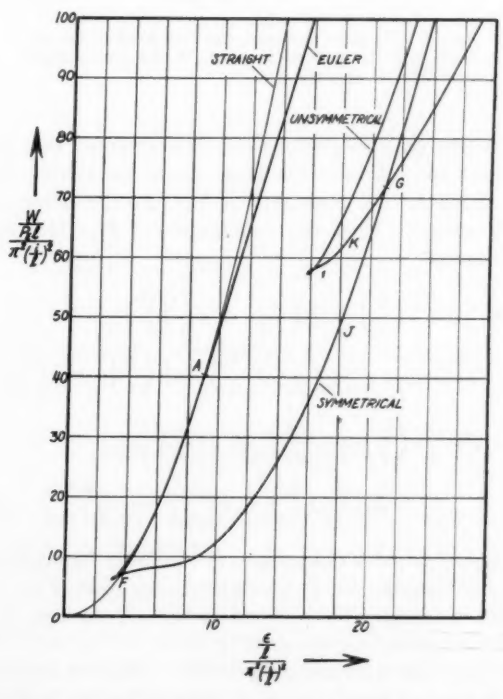

FIG. 5. Relation between the strain energy *W* stored in the system of a column with two equally spaced lateral supports and end shortening ϵ of the column.

librium positions for the column are first, straight unbuckled state from 0 to F (Fig. 5), then symmetrical buckled state from F to G, and finally unsymmetrical buckled state from G to H. Whenever a change in the type of the equilibrium positions occurs, there is a sudden jump in the value of the load P on the column. Thus when the column changes from straight to symmetrically buckled shape, the value of the end load P jumps from $3.75P_E$ to $0.63P_E$. When the column changes from symmetrical to unsymmetrical shape, the value of the end load P jumps from $7.95P_E$ to $5.26P_E$. The "Euler" three wave buckling does not come into the picture at all in this particular case. It is especially interesting to notice that the branch point of the equilibrium position, A, which in the classical theory of infinitesimal deflections is the only equilibrium position other than the straight unbuckled shape, may not appear in the testing procedure. The column might buckle at a load P only $3.75/9.00 = 0.417$ times the "classical" buckling load of $9P_E$. In the paper by Cox[4] and the author,[2] the lower buckling load of curved shells observed in the testing machine is attributed to the slight imperfections of the test specimens. The present finding seems to indicate that even with perfect specimens, it is possible to get a lower buckling load than that predicted by theory of infinitesimal deflection. The second interesting point is that the magnitude of the end load P really does not determine whether the corresponding equilibrium position is a probable one. In fact the correct solution is usually opposite to what one would generally expect. One would generally expect that at a given value of the end shortening ϵ, the state involving lower load P is the probable one to occur. However, a point J (Fig. 5) having a higher load P than the point K (Fig. 5) as can be seen from Fig. 4, is the probable equilibrium state.

It has been stated in the previous paragraph that for the case shown the "Euler" three wave buckling is not a probable state. If, however, the supporting springs are much stiffer, it is possible to have a W *vs.* ϵ diagram as shown in Fig. 6. Then the "Euler" three wave buckling is actually the first buckled shape to appear. The symmetrical buckling involving deflections of the supporting springs appears only after the end shortening is increased beyond the point J (Fig. 6).

Case of a Single Lateral Support, Effect of Initial Deflection

To simplify calculation, the case of a single lateral support located at center of the span is considered. Assuming that the initial deflection of the column can be represented by

$$w^0 = a_1^0 \sin (\pi x/l) \tag{52}$$

and the buckled form of the column again by Eq. (3), it is also assumed that the supporting spring is undeflected when the column is at its original state given by Eq. (52). Then by variational method the relation between the Fourier coefficients and spring forces is obtained as

$$\frac{a_1}{l} = \frac{\frac{2}{\pi^2}\frac{F}{P_E} - \frac{a_1^0}{l}}{\frac{P}{P_E} - 1} \tag{53}$$

and

$$\frac{a_n}{l} = \frac{2(-1)^{\frac{n-1}{2}}\frac{F}{P_E}}{n^2\pi^2\left(\frac{P}{P_E} - n^2\right)} \quad (n = 3, 5, 7)$$

By a similar method to that used to obtain Eq. (12),

$$\frac{\delta}{l} = \frac{a_1^0}{l}\left[\frac{P/P_E}{1 - (P/P_E)}\right] + K\frac{F}{P_E} \tag{54}$$

where δ is the deflection of the supporting spring, and using Eq. (18)

$$K = \frac{2}{\pi^2}\sum_{n=1,3,5}^{\infty}\frac{1}{n^2\left[\frac{P}{P_E} - n^2\right]} = \left\{\frac{1}{4} - \frac{1}{2\theta}\tan\frac{\theta}{2}\right\}\Big/\left(\frac{P}{P_E}\right) \tag{55}$$

The end shortening ϵ_1 due to buckling can be similarly obtained as

$$\frac{\epsilon_1}{l} = \frac{\frac{\pi^2}{4}\left(\frac{a_1^0}{l}\right)^2\left[1 - \left(\frac{P}{P_E} - 1\right)^2\right] - \frac{a_1^0}{l}\frac{F}{P_E}}{\left(\frac{P}{P_E} - 1\right)^2} + C\left(\frac{F}{P_E}\right)^2 \tag{56}$$

where

$$C = \frac{1}{\pi^2}\sum_{n=1,3,5}^{\infty}\frac{1}{n^2\left[\frac{P}{P_E} - n^2\right]^2} = \left\{\frac{3}{16} + \frac{1}{16}\tan^2\frac{\theta}{2} - \frac{3}{8\theta}\tan\frac{\theta}{2}\right\}\Big/\left(\frac{P}{P_E}\right)^2 \tag{57}$$

The shortening due to direct compression stress can be calculated by Eq. (31).

The bending strain energy of the column is

$$\frac{W_1}{P_E l} = \frac{\pi^2}{4}\frac{\frac{a_1^0}{l}\frac{P}{P_E}\left(\frac{a_1^0}{l}\frac{P}{P_E} - \frac{4}{\pi^2}\frac{F}{P_E}\right)}{\left(\frac{P}{P_E} - 1\right)^2} + B\left(\frac{F}{P_E}\right) \tag{58}$$

where

$$B = \frac{1}{\pi^2}\sum_{n=1,3}^{\infty}\frac{1}{\left[\frac{P}{P_E} - n^2\right]^2} = \left\{\frac{1}{16} + \frac{1}{16}\tan^2\frac{\theta}{2} - \frac{1}{8\theta}\tan\frac{\theta}{2}\right\}\Big/\left(\frac{P}{P_E}\right) \tag{59}$$

The strain energy due to direct compression and the

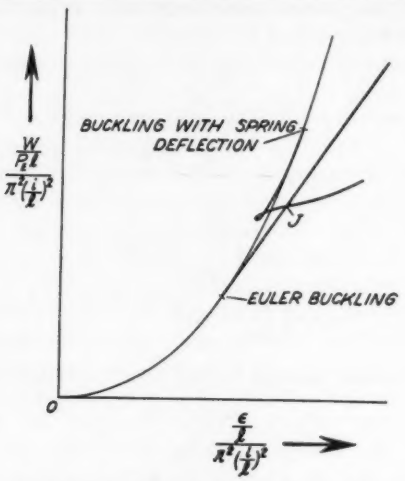

FIG. 6. Buckling of column started from Euler's type without deflection of the lateral supports.

strain energy stored in the supporting spring can be calculated by Eqs. (38) and (5), respectively.

As an example,

$$\frac{F}{P_E} = 13.712\,\frac{\delta}{l}\left(1 - 208.89\frac{\delta}{l} + 10{,}444\,\frac{\delta^2}{l^2}\right) \quad (60)$$

The shape of F *vs.* δ curve given by Eq. (60) is similar to that shown in Fig. 2, only the initial slope is made smaller. By substituting Eq. (60) into Eq. (54), a cubic equation for δ/l with a given value of P/P_E is obtained. When $a_1^0 = 0$, *i.e.*, the column is initially straight, this cubic equation has a root $\delta/l = 0$ representing unbuckled position. The branch point of the solution occurs at $P/P_E = 3.61$. The shape of the P *vs.* δ curve is shown in Fig. 7 where P/P_E is plotted against $\delta/\pi i$ and with $\pi i/l = 1/100$. When $a_1^0 \neq 0$, the curves do not have a branch point. Furthermore, with larger values of a_1^0, the maximum possible end load becomes smaller. For $a_1^0/\pi i = 0.1$ or $a_1^0/l = 0.001/\pi$, the maximum value of P/P_E is reduced from 3.61 to 1.82. This effect is shown clearly in Fig. 8, where the maximum value of P/P_E is plotted as a function of $a_1^0\pi/l$.

In Fig. 9, the end load P is plotted against the shortening ϵ. Without initial deflection, there is a part of the buckling curve which gives decreasing value of ϵ, such as LM. Thus within this range of values of ϵ, three equilibrium positions are possible for a fixed ϵ. But with increasing value of initial deflection, this part of the buckling curve gradually disappears, and only one equilibrium position is possible for a given value of ϵ. At $a_1^0/\pi i = 0.1$, this change in the character of the curve is already completed.

In Fig. 10, where the elastic energy of the system is plotted as a function of unit end shortening ϵ, the above mentioned change in type of buckling curve removes the possibility of a jump in the value of P/P_E at a certain stage of the buckling process which is indicated by a node point such as C (Fig. 10). Therefore, by introducing a sufficient amount of initial deflection, there is

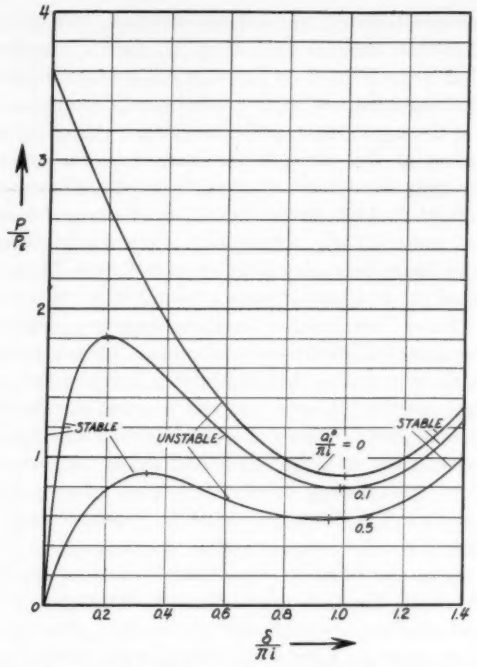

FIG. 7. Relation between the end load P on the column with various amounts of initial deflection a_1^0 and the deflection δ of a single lateral support at the middle.

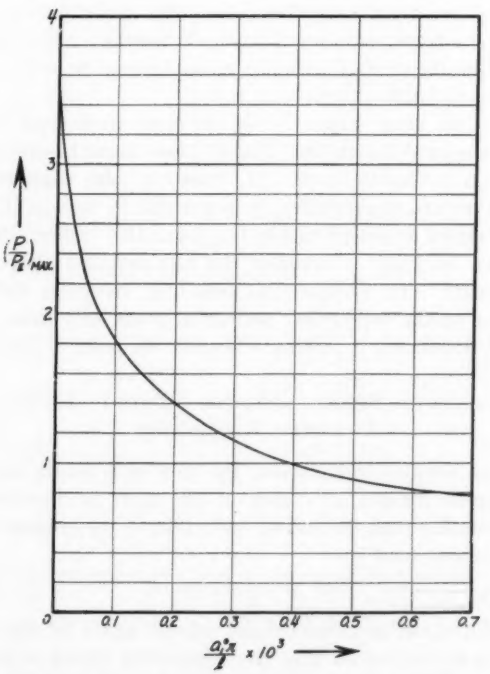

FIG. 8. The maximum end load P on the column as a function of its initial deflection a_1^0.

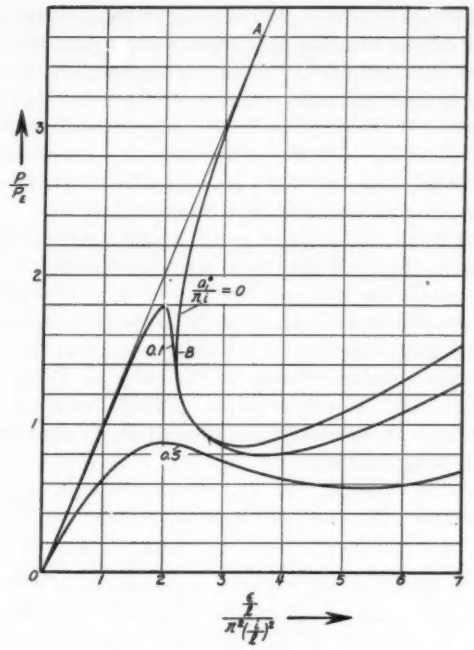

FIG. 9. Relation between the end load P on a column with a single lateral support at its middle and its end shortening ϵ.

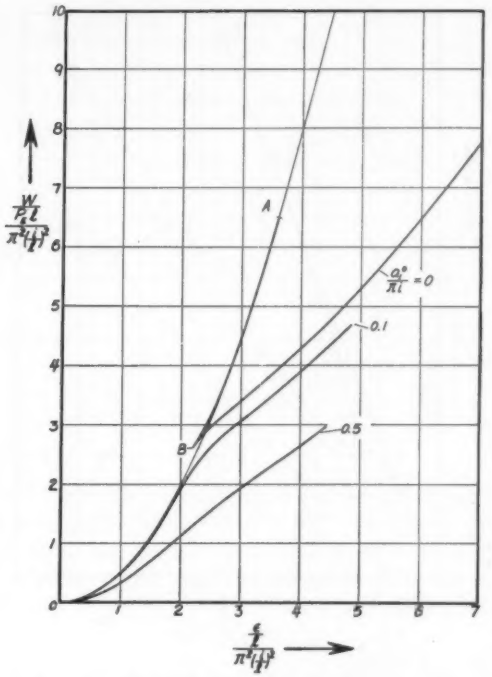

FIG. 10. Relation between the total strain energy W stored in the system of a column with a single lateral support and the end shortening ϵ of the column.

an apparent change in the buckling characteristics of the column.

CASE OF A SINGLE LATERAL SUPPORT, EFFECT OF ELASTICITY OF THE TESTING MACHINE

In the foregoing paragraphs, it has been assumed that the testing machine is completely rigid. In other words, if the loading crank of the machine is held at a fixed position, the distance between the end plates will be constant and not affected by the magnitude of forces acting on them. Actually, this is not true. The machine always has a certain amount of "yield" or "give." This characteristic of the testing machine can be represented by a spring placed between the specimen and the supposedly rigid end plate (Fig. 11). The deflection ϵ_3 of this spring can be assumed to be a linear function of the applied load P, *i.e.*,

$$\epsilon_3 = kP \tag{61}$$

Writing in terms of the Euler buckling load P_E,

$$\epsilon_3/l = (k/l)P_E(P/P_E) = (kEA/l)(\pi i/l)^2(P/P_E) \tag{62}$$

The elastic energy stored in this spring is

$$\frac{W_3}{P_E l} = \frac{1}{2}\left(\frac{kEA}{l}\right)\left(\frac{\pi i}{l}\right)^2\left(\frac{P}{P_E}\right)^2 \tag{63}$$

The total shortening ϵ of the column can be obtained as the sum $\epsilon_1 + \epsilon_2 + \epsilon_3$. For the case of a single lateral support, ϵ_1 and ϵ_2 are calculated by means of Eqs. (56) and (31). The total elastic energy is the sum $W_1 + W_2 + W_4 + W_5$ which can be calculated by means of Eqs. (58), (5), (39) and (63).

For the numerical example, $kEA/l = 3$, $\pi i/l = 1/100$ and a supporting spring with the property represented by Eq. (60). The results of the calculation are shown in Figs. 12 and 13. In Fig. 12, P/P_E is plotted against $(\epsilon/l)/(\pi i/l)^2$. In Fig. 13, $(W/P_E l)/(\pi i/l)^2$ is plotted

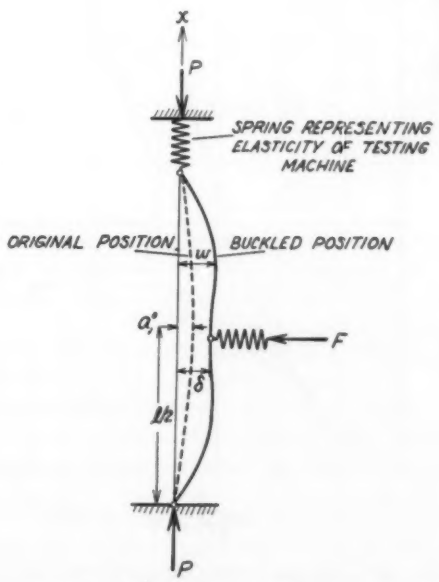

FIG. 11. Column with a single lateral support at its middle tested in a testing machine with certain amount of elasticity.

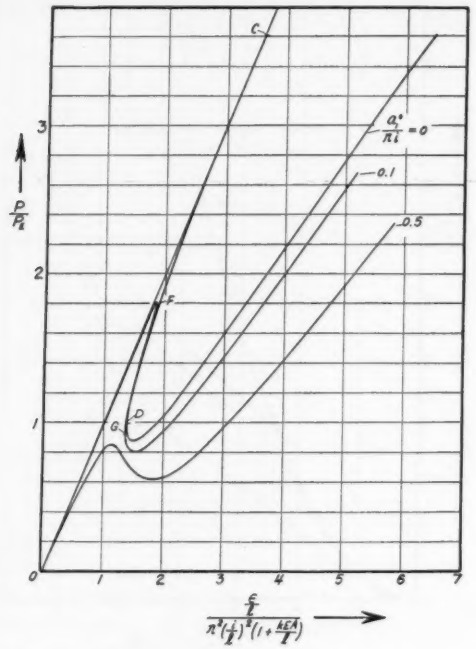

FIG. 12. Relation between the end load P on a column with a single lateral support at its middle and its end shortening ϵ, taking into account the elasticity of the testing machine. (Compare with Fig. 9.)

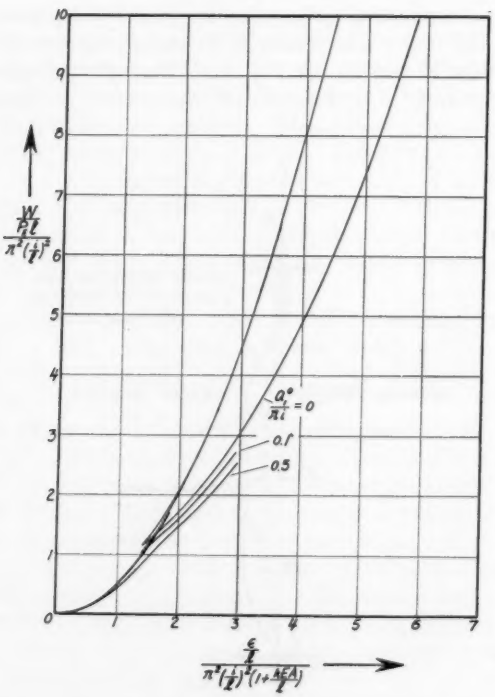

FIG. 13. Relation between the total strain energy W stored in the system of a column with a single lateral support and the end shortening ϵ of the column, taking into account the elasticity of the testing machine. (Compare with Fig. 10.)

against $(\epsilon/l)/(\pi i/l)^2$. For a straight column, the first possibility of buckling appears at a lower value of P/P_E due to the elasticity of the testing machine. If the machine is rigid, the jump occurs at $P/P_E = 2.40$ to $P/P_E = 1.09$. With $kEA/l = 3$, the jump occurs at $P/P_E = 1.62$ to $P/P_E = 0.89$. Therefore, the test buckling load of this type of column is profoundly affected by the elastic characteristics of the testing machine.

Furthermore, for $a_1^0/\pi i = 0.1$, a rigid testing machine excludes the possibility of a jump in equilibrium position, while for the case $kAE/l = 3$, Fig. 13 indicates the possibility of a jump at $(\epsilon/l)/(\pi i/l)^2 = 6.1$. By referring back to Fig. 12, it will be noted that the jump involves a sudden change of the value of P/P_E from 1.52 to 0.80. Hence, even the apparent buckling characteristics of the column are affected by the elasticity of the testing machine.

STABILITY OF THE EQUILIBRIUM POSITIONS UNDER INFINITESIMAL DISTURBANCES

The problem of stability in connection with the criterion of the most probable equilibrium position has been mentioned. If the column is unstable under infinitesimal disturbances, it is certainly unstable under finite disturbances. Therefore, a first step in the stability investigation is the determination of the stability under infinitesimal disturbances. This calculation will be carried out for the case of a single central lateral support.

The elastic energy stored in the system is the sum of the direct compression energy in the column and the loading spring representing the testing machine, the elastic energy due to bending, and the elastic energy stored in the lateral support. By means of Eqs. (4), (5), (39) and (63), this total energy can be expressed as

$$\frac{W}{P_E l} = \frac{\pi^2}{4}\left[\left(\frac{a_1 - a_1^0}{l}\right)^2 + \sum_{n=3,5,F}^{\infty} n^4\left(\frac{a_n}{l}\right)^2\right] + \frac{1}{2}\left(\frac{P_E}{AE} + \frac{kP_E}{l}\right)\left(\frac{P}{P_E}\right)^2 + \int_0^{s/l}\frac{F}{P_E}\,d\xi \quad (64)$$

The end shortening due to bending can be calculated by

$$(1/2)\int_0^l \left(\frac{dw}{dx}\right)^2 dx$$

and thus the total end shortening ϵ is

$$\frac{\epsilon}{l} = \frac{\pi^2}{4}\left[\sum_{n=1,3,5}^{\infty} n^2\left(\frac{a_n}{l}\right)^2 - \left(\frac{a_1^0}{l}\right)^2\right] + \left(\frac{P_E}{AE} + \frac{kP_E}{l}\right)\frac{P}{P_E} \quad (65)$$

The variations of $W/P_E l$ with respect to a_n have to conform to the geometrical constraint which can be expressed as

$$\epsilon/l = \text{constant} \quad (66)$$

The equilibrium conditions are obtained by setting the first derivatives of $W/P_E l$ with respect to a_n equal to

zero, taking into account the condition Eq. (66). These equilibrium conditions are, of course, the same as those obtained before. Since these first derivatives are zero at equilibrium position, the total elastic energy for configurations near the equilibrium position can be expanded into a Taylor series of a_n in the following manner:

$$\frac{W}{P_E l} = \left(\frac{W}{P_E l}\right)_{a_n = a_n^*} + \frac{1}{2} \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} A_{nm} (a_n - a_n^*)(a_m - a_m^*) \quad (67)$$

where a_n^* is the value of a_n at equilibrium position, and

$$A_{nm} = \frac{\partial^2 (W/P_E l)}{\partial a_n \, \partial a_m} \text{ at } a_n = a_n^*, \, a_m = a_m^* \quad (68)$$

Terms not explicitly written in Eq. (67) are terms involving $(a_n - a_n^*)$ in higher orders than second. For infinitesimal disturbances, or infinitesimal values of $(a_n - a_n^*)$, the higher order terms can be neglected. Then the elastic energy $W/P_E l$ for configurations near the equilibrium position will be larger or smaller than the elastic energy at the equilibrium position, depending upon whether the double sum in Eq. (67) is positive or negative. Therefore, if the double sum is always positive for any values of $(a_n - a_n^*)$ the equilibrium position is stable. In other words, the equilibrium is a stable one only when the double sum in Eq. (67) is positive definite. If

$$\Delta_1 = A_{11}, \quad \Delta_2 = \begin{vmatrix} A_{11} & A_{13} \\ A_{31} & A_{33} \end{vmatrix}, \quad \Delta_3 = \begin{vmatrix} A_{11} & A_{13} & A_{15} \\ A_{31} & A_{33} & A_{35} \\ A_{51} & A_{53} & A_{55} \end{vmatrix} \cdots$$

$$\Delta_g = \begin{vmatrix} A_{11} & A_{13} & \cdots & A_{1(2g-1)} \\ A_{31} & A_{33} & \cdots & A_{3(2g-1)} \\ \cdots & \cdots & \cdots & \cdots \\ A_{(2g-1)1} & A_{(2g-1)3} & \cdots & A_{(2g-1)(2g-1)} \end{vmatrix} \quad (69)$$

Then it is well-known that the conditions for the double sum in Eq. (67) to be positive definite are $\Delta_1 > 0$, $\Delta_2 > 0$, $\Delta_3 > 0, \ldots, \Delta_g > 0, \ldots$.

From Eqs. (64) and (65)

$$A_{11} = \frac{\pi^2}{2}\left(1 - \frac{P}{P_E}\right) + \frac{d\left(\frac{F}{P_E}\right)}{d\zeta} + \frac{1}{\left(\frac{P_E}{AE} + \frac{kP_E}{l}\right)} \frac{\left(\frac{F}{P_E} - \frac{\pi^2}{2}\frac{a_1^0}{l}\right)^2}{\left(\frac{P}{P_E} - 1\right)^2}$$

$$A_{1n} = A_{n1} = -(-1)^{\frac{1+n}{2}} \left\{ \frac{d\left(\frac{F}{P_E}\right)}{d\zeta} + \frac{1}{\left(\frac{P_E}{AE} + \frac{kP_E}{l}\right)} \times \frac{\left(\frac{F}{P_E} - \frac{\pi^2}{2}\frac{a_1^0}{l}\right)\frac{F}{P_E}}{\left(\frac{P}{P_E} - 1\right)\left(\frac{P}{P_E} - n^2\right)} \right\}$$

$$A_{nn} = \frac{\pi^2}{2} n^2 \left(n^2 - \frac{P}{P_E}\right) + \left\{ d\frac{\frac{F}{P_E}}{d\zeta} + \frac{1}{\left(\frac{P_E}{AE} + \frac{kP_E}{l}\right)} \frac{\left(\frac{F}{P_E}\right)^2}{\left(\frac{P}{P_E} - n^2\right)^2} \right\}$$

$$A_{nm} = -(-1)^{\frac{m+n}{2}} \left\{ \frac{d\left(\frac{F}{P_E}\right)}{d\zeta} + \frac{1}{\left(\frac{P_E}{AE} + \frac{kP_E}{l}\right)} \frac{\left(\frac{F}{P_E}\right)^2}{\left(\frac{P}{P_E} - n^2\right)\left(\frac{P}{P_E} - m^2\right)} \right\} \quad (70)$$

where $\zeta = \delta/l$.

First the simpler case of a very elastic testing machine is investigated. This means that $k \to \infty$, as can be seen easily from Eq. (61). Then the last terms in each of the expressions in Eq. (70) drop out. The determinants defined by Eq. (69) are found to be as follows:

$$\Delta_1 = \left\{ 1 + \frac{d\left(\frac{F}{P_E}\right)}{d\zeta} \left[\frac{2}{\pi^2} \frac{1}{\left(1 - \frac{P}{P_E}\right)} \right] \right\} \frac{\pi^2}{2}\left(1 - \frac{P}{P_E}\right)$$

$$\Delta_2 = \left\{ 1 + \frac{d\left(\frac{F}{P_E}\right)}{d\zeta} \left[\frac{2}{\pi^2} \frac{1}{\left(1 - \frac{P}{P_E}\right)} + \frac{2}{\pi^2} \frac{1}{9\left(9 - \frac{P}{P_E}\right)} \right] \right\} \times \frac{\pi^2}{2}\left(1 - \frac{P}{P_E}\right) \frac{\pi^2}{2} 9\left(9 - \frac{P}{P_E}\right) \quad (71)$$

or

$$\Delta_g = \left\{ 1 + \frac{d\left(\frac{F}{P_E}\right)}{d\zeta} \sum_{n=1,3,5}^{n=2g-1} \frac{2}{\pi^2} \frac{1}{n^2\left(n^2 - \frac{P}{P_E}\right)} \right\} \times \prod_{n=1,3,5}^{n=2g-1} \frac{\pi^2}{2} n^2 \left(n^2 - \frac{P}{P_E}\right)$$

Now take the case $\zeta = 0$ first, *i.e.*, the unbuckled straight equilibrium positions. Here $d(F/P_E)/d\zeta$ is the initial slope of supporting force curve which is positive. For $0 < P/P_E < 1$, the multiplying factor before the curly bracket is also positive. Furthermore, each term under the summation sign is positive. Therefore, every quantity which appears in Δ_g is positive and hence Δ_g is positive. Consequently the equilibrium positions are stable. By direct computation, using the value of $d(F/P_E)d\zeta = 13.712$ as given by Eq. (60), it is found that the straight unbuckled equilibrium positions are stable under infinitesimal disturbances if $P/P_E < 3.610$, the branch point of equilibrium positions. For $\zeta \neq 0$, it is found that the stability is indicated by the sign of Δ_g with $g \to \infty$, *i.e.*, all the determinant

changes sign if $Lim\ \Delta_g$ changes sign. Now as stated above, the multiplying factor before the curly bracket is positive when $0 < P/P_E < 1$ and negative when $1 < P/P_E < 9$; therefore, the attention of the reader need only be fixed on the quantities within the curly bracket. When $g \to \infty$, the series in Eq. (60) can be summed and

$$1 + \frac{d\left(\frac{F}{P_E}\right)}{d\zeta} \sum_{n=1,3,5}^{\infty} \frac{2}{\pi^2} \frac{1}{n^2\left(n^2 - \frac{P}{P_E}\right)} = 1 - \frac{d\left(\frac{F}{P_E}\right)}{d\zeta} \frac{1}{\left(\frac{P}{P_E}\right)} \left(\frac{1}{4} - \frac{1}{2\Theta} \tan \frac{\Theta}{2}\right) \quad (72)$$

The limiting case between stability and instability is, of course, when the expression on the left of Eq. (72) is zero. Therefore, for the limiting case between stability and instability

$$\frac{d\zeta}{d(F/P_E)} = \frac{1}{(P/P_E)} \left(\frac{1}{4} - \frac{1}{2\Theta} \tan \frac{1}{2}\right) \quad (73)$$

The meaning of this condition can be understood better by finding the corresponding value of $d\zeta/d\,(P/P_E)$ which is the reciprocal of the slope of P/P_E *vs.* δ/l curve as shown in Fig. 7. Eq. (73) can be rewritten as

$$\frac{d\zeta}{d(P/P_E)} = \frac{d(F/P_E)}{d(P/P_E)} \frac{1}{(P/P_E)} \left(\frac{1}{4} - \frac{1}{2\Theta} \tan \frac{\Theta}{2}\right) \quad (74)$$

Now differentiating Eq. (54) which is true for equilibrium positions,

$$\frac{d\zeta}{d\left(\frac{P}{P_E}\right)} = \frac{a_1^0}{l} \frac{1}{\left(1 - \frac{P}{P_E}\right)^2} + \left\{\frac{d\left(\frac{F}{P_E}\right)}{d\left(\frac{P}{P_E}\right)} - \frac{\frac{F}{P_E}}{\frac{P}{P_E}}\right\} \times \frac{\frac{1}{4} - \frac{1}{2\Theta} \tan \frac{\Theta}{2}}{\left(\frac{P}{P_E}\right)} + \frac{\frac{F}{P_E}}{\left(\frac{P}{P_E}\right)^2} \times \left\{-\frac{1}{8} + \frac{1}{4\Theta} \tan \frac{\Theta}{2} - \frac{1}{8} \tan^2 \frac{\Theta}{2}\right\} \quad (75)$$

Substituting the value of $d(F/P_E)/(P/P_E)$ from Eq. (74) into Eq. (75),

$$\frac{d\zeta}{d\left(\frac{P}{P_E}\right)} = \frac{d\zeta}{d\left(\frac{P}{P_E}\right)} + \frac{a_1^0}{l} \frac{1}{\left(1 - \frac{P}{P_E}\right)^2} - \frac{\frac{F}{P_E}}{\left(\frac{P}{P_E}\right)^2} \times \left\{\frac{3}{8} - \frac{3}{4\Theta} \tan \frac{\Theta}{2} + \frac{1}{8} \tan^2 \frac{\Theta}{2}\right\} \quad (76)$$

Eq. (76) can be satisfied by either

$$d\zeta/d(P/P_E) = \infty,\ i.e.,\ d(P/P_E)/d\zeta = 0 \quad (77)$$

or

$$0 = \frac{a_1^0}{l} \frac{1}{\left(1 - \frac{P}{P_E}\right)^2} - \frac{\frac{F}{P_E}}{\left(\frac{P}{P_E}\right)^2} \times \left\{\frac{3}{8} - \frac{3}{4\Theta} \tan \frac{\Theta}{2} + \frac{1}{8} \tan^2 \frac{\Theta}{2}\right\} \quad (78)$$

It is found that Eq. (78) cannot be satisfied with any of the equilibrium states. Therefore, for a very elastic testing machine the transition point from stable equilibrium positions to unstable equilibrium positions or *vice versa* is characterized by the condition Eq. (77), *i.e.*, the slope of the P/P_E *vs.* δ/l curve must be horizontal. This condition is utilized to mark the stable and the unstable regions in Fig. 7.

With $k \to \infty$, the deflection of the loading spring representing the elasticity of the testing machine is very large compared with the shortening of the specimen. Therefore, the force in the spring, which is equal to load on the specimen, is not influenced by the small variation of shortening of the specimen. Similar situation exists also for a column loaded by a dead weight. Therefore, the stability criterion given by Eq. (77) also applies for such cases.

For the case $k \neq \infty$, the calculation for stability is more complicated. To simplify the calculation, let $a_1^0 = 0$, *i.e.*, assuming the column is initially straight. Using the values of A_{nm} given by Eq. (70), it is found that g-th determinant is

$$\Delta_g = \left[1 + \left(\frac{\frac{F}{P_E}}{\frac{\pi i^*}{l}}\right)^2 \frac{2}{\pi^2} \sum_{n=1,3,5}^{2g-1} \frac{1}{n^2\left(n^2 - \frac{P}{P_E}\right)^3} + \frac{d\left(\frac{F}{P_E}\right)}{d\zeta} \left\{\frac{2}{\pi^2} \sum_{n=1,3,5}^{2g-1} \frac{1}{n^2\left(n^2 - \frac{P}{P_E}\right)} + \left(\frac{\frac{F}{P_E}}{\frac{\pi i^*}{l}}\right)^2 \left(\frac{2}{\pi^2}\right)^2 \times \left[\sum_{n=1,3,5}^{2g-1} \frac{1}{n^2\left(n^2 - \frac{P}{P_E}\right)^3} \sum_{m=1,3,5}^{2g-1} \frac{m^2}{\left(m^2 - \frac{P}{P_E}\right)^3} - \left(\sum_{n=1,3,5}^{2g-1} \frac{1}{\left(n^2 - \frac{P}{P_E}\right)^3}\right)^2\right]\right\}\right] \prod_{n=1,3,5}^{2g-1} \frac{\pi^2}{2} n^2 \left(n^2 - \frac{P}{P_E}\right) \quad (79)$$

where $(\pi i^*/l)^2 = (P_E/AE) + (kP_E/l)$.

All the straight unbuckled configurations are again found to be stable up to $P/P_E = 3.61$ for the particular case investigated. In other words, straight equilibrium states are stable under infinitesimal disturbances up to the branch point at which buckling begins. For equilibrium states involving buckling we again fix our attention on the quantities within the curly bracket in the expression for Δ_g, Eq. (79). It is again found that the sign of Δ_g when $g \to \infty$ is representative for the transi-

tion from stability to instability or *vice versa*. When $g \to \infty$, all the series in Eq. (79) can be summed and the condition of transition of stability is obtained

$$1 - \left(\frac{\frac{F}{P_E}}{\frac{\pi i^*}{l}}\right)^2 \frac{1}{\left(\frac{P}{P_E}\right)^3}\left[\frac{1}{4} + \frac{7}{32}\sec^2\frac{\Theta}{2} - \frac{15}{16\Theta}\tan\frac{\Theta}{2} - \frac{1}{16}\frac{\Theta}{2}\tan\frac{\Theta}{2}\sec^2\frac{\Theta}{2}\right] - \frac{1}{\left(\frac{P}{P_E}\right)}\frac{d\left(\frac{F}{P_E}\right)}{d\zeta}\left[\left\{\frac{1}{4} - \frac{1}{2\Theta}\tan\frac{\Theta}{2}\right\} + \left(\frac{\frac{F}{P_E}}{\frac{\pi i^*}{l}}\right)^2 \frac{1}{128\left(\frac{P}{P_E}\right)^3}\left\{\frac{\tan\frac{\Theta}{2}}{\frac{\Theta}{2}}\left(3\frac{\tan\frac{\Theta}{2}}{\frac{\Theta}{2}} - 5\sec^2\frac{\Theta}{2} - 1\right) + \sec^2\frac{\Theta}{2}\left(3 + 2\frac{\Theta}{2}\tan\frac{\Theta}{2}\right)\right\}\right] = 0 \quad (80)$$

Since

$$\frac{d\zeta}{d\left(\frac{P}{P_E}\right)} = \frac{d\left(\frac{F}{P_E}\right)\Big/ d\left(\frac{P}{P_E}\right)}{d\left(\frac{F}{P_E}\right)\Big/ d\zeta}$$

from (75),

$$\frac{1}{\left(\frac{P}{P_E}\right)}\frac{d\frac{F}{P_E}}{d\zeta} = \frac{d\left(\frac{F}{P_E}\right)\Big/ d\left(\frac{P}{P_E}\right)}{\left\{\frac{d\left(\frac{F}{P_E}\right)}{d\left(\frac{P}{P_E}\right)}\Big/\frac{F}{P_E} - \frac{1}{\frac{P}{P_E}}\right\}\left\{\frac{1}{4} - \frac{1}{4}\frac{1}{\frac{\Theta}{2}}\tan\frac{\Theta}{2}\right\} + \frac{1}{8\frac{P}{P_E}}\left\{\frac{1}{\frac{\Theta}{2}}\tan\frac{\Theta}{2} - \sec^2\frac{\Theta}{2}\right\}} \quad (81)$$

By substituting Eq. (81) into Eq. (80), it is found that the condition for transition of stability is given by either

$$2 + \sec^2(\Theta/2) - 3\frac{1}{(\Theta/2)}\tan(\Theta/2) = 0 \quad (82)$$

or

$$\left(\frac{\pi i^*}{l}\right)^2 + \frac{d}{d\left(\frac{P}{P_E}\right)}\left\{\left(\frac{\frac{F}{P_E}}{\frac{P}{P_E}}\right)^2 \times \left(\frac{3}{16} + \frac{1}{16}\tan^2\frac{\Theta}{2} - \frac{3}{8\Theta}\tan\frac{\Theta}{2}\right)\right\} = 0 \quad (83)$$

Here again the condition represented by Eq. (82) cannot be satisfied by any of the equilibrium positions. Therefore, the only condition left for the transition of stability is that given by Eq. (83). By means of Eqs. (56), (31) and (62), the total end shortening including the shortening of the loading spring is

$$\frac{\epsilon}{l} = \left(\frac{\pi i^*}{l}\right)^2 \frac{P}{P_E} + \left(\frac{\frac{F}{P_E}}{\frac{P}{P_E}}\right)^2 \times \left(\frac{3}{16} + \frac{1}{16}\tan^2\frac{\Theta}{2} - \frac{3}{8\Theta}\tan\frac{\Theta}{2}\right) = 0 \quad (84)$$

Therefore, the condition given by Eq. (83) is simply

$$d(\epsilon/l)/d(P/P_E) = 0, \text{ or } d(P/P_E)/d(\epsilon/l) = \infty \quad (85)$$

Hence, the transition from stable equilibrium to unstable equilibrium or *vice versa* under infinitesimal disturbances occurs at points on the P/P_E *vs.* ϵ/l curves where the slope is vertical. Therefore, if the testing machine is rigid, Fig. 9 shows that for the case $a_1^0/\pi i = 0$, there is an unstable region between the points A and B (Fig. 9). However, for the cases $a_1^0/\pi i = 0.1$ and $a_1^0/\pi i = 0.5$, there is no unstable equilibrium position. If the testing machine has a certain amount of elasticity, *e.g.*, $kEA/l = 3$, then Fig. 12 shows that for $a_1^0/\pi i = 0$ there is an unstable region between the points C and D (Fig. 12). Similarly for $a_1^0/\pi i = 0.1$, the equilibrium positions are unstable between the points F and G (Fig. 12). However, for $a_1^0/\pi i = 0.5$, all the equilibrium positions are stable.

The conditions found in this section for transition between stable equilibrium to unstable equilibrium under infinitesimal disturbances appear in very simple form and do not involve any parameter which is characteristic of the particular problem concerned. Therefore, it is possible that although these rules are derived from particular cases, they hold for all non-linear buckling problems of this category. This surmise has to be proved, of course, by further investigation.

Conclusions

In the previous papers,[1, 2, 3] an explanation for the discrepancy between the classical theory of thin shells with infinitesimal deflections and the experimental result is suggested. It is stated then that there are equilibrium positions of the shell which involve much lower values of external load than the buckling load predicted by the classical theory. The initial imperfection of the shell tends to lower the maximum load the shell can sustain. The lower experimental buckling load is thus attributed to the slight imperfections always present in the test specimens. Furthermore, the elastic characteristics of the testing machine are shown to have profound effect on the buckling process. In the present paper these statements are subject to a quantitative verification not by attacking the shell problem itself

which is too complicated, but by solving the similar problem of a column supported laterally by non-linear springs.

However, a new interesting fact is found. With supporting springs whose characteristic simulates that found in the case of a curved shell, a straight unbuckled column may have an elastic energy and end shortening equal to those of a buckled state with finite deflection even at a load far below the classical buckling load. If the end plates of the testing machine are brought slightly nearer, the elastic energy for the unbuckled state will be higher than the buckled state. Therefore, at a small disturbance, the column will jump to the buckled equilibrium state. This means that the recorded buckling load in a testing machine can be lower than that of classical theory even for a perfect specimen without initial deflection. This critical point can be further lowered by the elasticity of the testing machine. Hence, it seems that the buckling load calculated by means of classical theory really has very little bearing on the actual load carrying ability of this type of structure.

At the jumping point of equilibrium states, both the initial equilibrium and the final equilibrium states are stable under infinitesimal disturbances. The question then arises as to how large the external impulse has to be in order for the column to leave the initial stable state. Take, for instance, the point C in Fig. 10. This point represents two equilibrium states, namely, the straight unbuckled state and the buckled state. Both are stable under infinitesimal disturbances and have the same amount of elastic energy. At the same end shortening ϵ, there is another equilibrium state in the curve AB, which has a slightly higher elastic energy. For this particular value of end shortening, the elastic energy W given by Eq. (64) can be plotted as a surface over the plane with coordinates $a_1, a_3, \ldots, a_\infty$. The load P is determined by the condition that the end shortening must be constant. Then the two stable equilibrium states will be represented by two minimum points. One of these points corresponding to the unstabled state is located at the origin of the $a_1, a_3, \ldots, a_\infty$ plane. Between these two minimum points will be a saddle point representing the unstable equilibrium state with a slightly higher elastic energy. (The unstable equilibrium state being represented by a saddle point follows from the fact that $\Delta_1, \Delta_2, \ldots, \Delta_\infty$ are all negative.) Therefore, the necessary external impulse is equal to or larger than the difference between the elasiic energy at the saddle point and the minimum points. For the case of point C in Fig. 10, this difference ΔW is

$$\Delta W \cong 0.15\pi^2 P_E(i^2/l)$$

For a 24SRT column of 0.09-inch thickness, 0.375-inch width and 19-inch length (tests were made on a column of this size[3]),

$$\Delta W = 3.26 \times 10^{-4} \text{ inch-lbs.}$$

which is very small indeed. This is, perhaps, sufficient to explain the "jumping" at point C.

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Shear Distribution Among Three or More Shear Webs

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Introduction

The distribution of the resultant shear force among the shear webs of a metal wing depends upon the shear stresses due to bending, that is, upon the longitudinal shear stresses and the corresponding equal transverse shear stresses. The variation of shear stress in a leading-edge wing beam was first given approximately by Newell[1] and more exactly by the author.[2] Subsequently, the author[3] gave a solution for the distribution of shear stress in a metal wing with two or more shear webs. Since the method of reference 3 is very laborious when there are more than two shear webs, a shorter method, even though less accurate, should be of considerable use to the airplane designer.

The shear webs of a metal wing do not carry all the vertical shear force on the wing because some of the shear load is carried by each segment of the skin that is not horizontal. It would be on the side of safety to assume that the entire vertical shear force on the wing is carried by the shear webs. With this assumption, the distribution of the resultant shear force at any cross-section to two shear webs could be determined from the fact that the sum of these two shear forces equals the resultant shear force and their moment about any point equals the moment of the resultant shear force about the same point. With more than two shear webs the Principle of Least Work would also have to be employed. The case of three shear webs, based upon the assumption that the shear webs carry all the vertical shear, will be worked out in detail. The procedure for a wing with four or more shear webs will then be outlined. In each analysis only the case of tension-field shear webs will be considered.

Work of Shear in a Tension-Field Shear Web

Fig. 1 shows a trapezoidal tension-field shear web subjected to an up load. Let OH be the median line of the shear web, DG (or h) the height of the web at distance x from vertex O and EF a wrinkle of length L which makes an angle α with the horizontal. Let t be the thickness of the web, S the shear force on cross-section DG, τc the shear stress at the midpoint of DG and σ the tensile stress in wrinkle EF. It is well known that σ is constant for all points along EF and has the value

$$\sigma = 2\tau_c/\sin 2\alpha \tag{1}$$

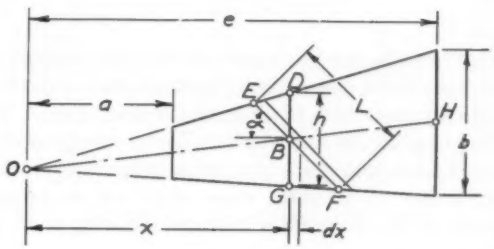

Fig. 1.

In reference 4 it was shown that in a tapered shear web of the dimensions usually found in wings τ_c is closely approximated by the average shear stress on section DG, or

$$\tau_c = S/th \tag{2}$$

Consider a strip of skin of length EF (or L) having dx as the horizontal distance between its two sides (Fig. 1). Its cross-sectional area is $tdx \sin \alpha$, and the work done in the strip by the tensile stress σ is

$$dW = \sigma^2 L(tdx \sin \alpha)/2E \tag{3}$$

where E is the modulus of elasticity. Hence, from Eqs. (1), (2) and (3), the work of shear in the entire shear web is

$$W = \int_a^e dW = \int_a^e (2S^2 L \sin \alpha/Eth^2 \sin^2 2\alpha)dx \tag{4}$$

Three Shear Webs

Let subscripts 1, 2 and 3 refer to the front, middle and rear shear webs, respectively. Thus, S_1, S_2 and S_3 are the shear forces in the front, middle and rear webs, respectively (Fig. 2). Let S_t be the resultant shear force on any cross-section of the wing. Let a_1, a_2 and a_t be the distances from the rear shear web to S_1, S_2 and S_t, respectively, and let a_t be positive when S_t is in front of the rear shear web (Fig. 2). From Fig. 2

$$S_1 + S_2 + S_3 = S_t \tag{5}$$

$$a_1S_1 + a_2S_2 = a_tS_t \tag{6}$$

Let

$$S_1/S_t = k \tag{7}$$

Then, from Eqs. (5), (6) and (7)

$$S_2/S_t = (a_t - ka_1)/a_2 \tag{8}$$

$$S_3/S_t = \{k(a_1 - a_2) + (a_2 - a_t)\}/a_2 \tag{9}$$

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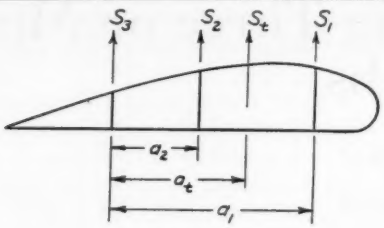

FIG. 2.

Fig. 1 can be used to represent the front, middle and rear shear webs, respectively, if subscripts 1, 2 and 3, respectively, are added to the letters of that figure. Thus b_1, b_2 and b_3 are the three heights at the wing root of the front, middle and rear shear webs, respectively. Since the vertices of all three shear webs will be approximately at the same distance from the wing root, it is evident from Fig. 1 that

$$h_1/b_1 = h_2/b_2 = h_3/b_3 \tag{10}$$

The angle between the horizontal and the upper and lower sides of a shear web in any actual airplane wing is always small. Hence, triangles $B_1E_1D_1$, $B_2E_2D_2$ and $B_3E_3D_3$ (Fig. 1) are similar triangles to a close approximation. This is also true of triangles $B_1F_1G_1$, $B_2F_2G_2$ and $B_3F_3G_3$. Then, to a close approximation

$$L_1/h_1 = L_2/h_2 = L_3/h_3 \tag{11}$$

It will be convenient to let

$$A_1 = b_1t_1,\ A_2 = b_2t_2,\ A_3 = b_3t_3 \tag{12}$$

$$J = b_1 \int_a^e (2S_t^2L_1 \sin \alpha_1/Eh_1^2 \sin^2 2\alpha_1)dx \tag{13}$$

In practically all airplanes the ratio a_1/a_2 (Fig. 2) is constant for all cross-sections of the wing. Moreover, it is approximately true that a_t/a_2 is also constant for all cross-sections. With these two ratios practically constant it is reasonable to assume that the ratios S_1/S_t, S_2/S_t and S_3/S_t (Fig. 2) are also approximately constant for all values of x. Then, from Eqs. (4), (12) and (13) the work done in the front shear web is

$$W_1 = \int_a^e (2S_1^2L_1 \sin \alpha_1/Et_1h_1^2 \sin^2 2\alpha_1)dx = (S_1/S_t)^2J/A_1 \tag{14}$$

Experiments have shown that shear webs as usually constructed have their wrinkles at practically the same angle with the horizontal; that is,

$$\alpha_1 = \alpha_2 = \alpha_3 \tag{15}$$

By means of Eqs. (4), (10), (11), (12), (13) and (15) it can be shown that the work in the middle and rear shear webs are, respectively,

$$W_2 = (S_2/S_t)^2J/A_2 \tag{16}$$

$$W_3 = (S_3/S_t)^2J/A_3 \tag{17}$$

By virtue of Eqs. (7), (8), (9), (14), (16) and (17) the total work W in the three shear webs, which equals $W_1 + W_2 + W_3$, can be written in the form

$$Wa_2^2/J = k^2a_2^2/A_1 + (a_t - ka_1)^2/A_2 + \{k(a_1 - a_2) + (a_2 - a_t)\}^2/A_3 \tag{18}$$

The value of k can now be determined from $\partial W/\partial k = 0$, or, since a_2 and J are constants, from $\partial(Wa_2^2/J)/\partial k = 0$. This last condition applied to Eq. (18) gives

$$k = \frac{a_ta_1/A_2 + (a_t - a_2)(a_1 - a_2)/A_3}{a_2^2/A_1 + a_1^2/A_2 + (a_1 - a_2)^2/A_3} \tag{19}$$

Eq. (19) depends upon the assumption that the ratio a_t/a_2 (Fig. 2) is constant for all values of x. Since the ratio a_2/(wing chord) is generally constant at each cross-section, this is equivalent to assuming that a_t/(wing chord) is also constant. Actually, a_t/(wing chord) may vary somewhat from section to section. When this occurs, the proper value of a_t to use in Eq. (19) can be obtained by drawing the straight line at a constant fraction of the chord which most nearly fits the position at each cross-section of the resultant of the air and inertia forces per unit length of span. This procedure is analogous to that of finding the elastic axis from experimentally determined elastic centers at various cross-sections.

Four or More Shear Webs

The procedure for four shear webs is analogous to that for three, except that $S_1/S_t = k_1$ and $S_2/S_t = k_2$. Then, S_3/S_t and S_4/S_t can be expressed in terms of k_1 and k_2 by means of equations analogous to Eqs. (5) and (6). After W has been found, k_1 and k_2 are obtained from $\partial W/\partial k_1 = 0$ and $\partial W/\partial k_2 = 0$.

Each shear web in excess of four requires an additional k and an additional $\partial W/\partial k = 0$.

Example

Let $A_2 = 0.9A_1$, $A_3 = 0.75A_1$, $a_1 = 0.5c$, $a_2 = 0.25c$, $a_t = 0.3c$ (Fig. 2), where c is the chord of the cross-section in question. From Eqs. (19), (8) and (9), respectively,

$$k = [(0.15/0.9 + 0.0125/0.75)c^2/A_1] \div (0.0625/1 + 0.25/0.9 + 0.0625/0.75)c^2/A_1 = 0.433$$

$$S_2/S_t = (0.3c - 0.433 \times 0.5c)/0.25c = 0.334$$

$$S_3/S_t = (0.443 \times 0.25c - 0.05c)/0.25c = 0.233$$

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Eccentricity in Columns

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SUMMARY

By relating eccentricity to slope at the end of a column, the mechanism of eccentricity behavior in flat-end loadings is discussed.

For both flat-end and pin-end cases, explanation is offered for the experimentally observed tendency, at failing loads, for the grouping ec/r^2 (called γ) to assume a value below a definite maximum.

Two non-dimensional graphical representations of the load-maximum stress relation for columns are given, and values of length and γ are stated for use with such charts, which can be employed to solve most column problems involving primary failure by translation, regardless of slenderness ratio or material involved.

SYMBOLS

A = area of cross-section of the column
c = distance of extreme filament from the neutral axis
e = eccentricity of loading
E = modulus of elasticity
$K = \sqrt{P/EI}$
L = total length of column between supports
P = load
r = radius of gyration of cross-section of column
S = stress at point indicated by subscript
$\gamma = ec/r^2$
Θ_T = slope of the axis of the column at the ends

INTRODUCTION

IN THE DESIGN of beam-columns it is customary for designers to use stress as a criterion, recognizing that stress depends on the applied terminal couples or the eccentricity of the loads applied at the ends of the beam-column. Applying the same approach to columns, if we can arrive at a notion of the maximum magnitude of the eccentricity, then we can find the load which sets up any stress considered critical; applying a safety factor to that load we can arrive at a design load.

When existing column formulas for steel, aluminum alloys, and other materials are compared with theoretical curves for eccentrically loaded columns, it is found that all of them correspond to essentially the same value of the non-dimensional parameter ec/r^2. The present paper is an attempt to explain why this is so and the conclusions summarized and analyzed in this paper are based on a large number of experiments in which the terminal slopes were measured as an indirect measure of the eccentricities present.

For a column subjected to loads of equal eccentricities, as in Fig. 1, the well-known expression for maximum stress is

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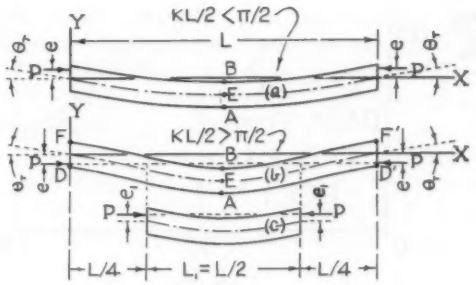

FIG. 1. Load diagram on which Figs. 2 and 3 are based.

$$S_{B,A} = (P/A)[1 \pm (ec/r^2) \sec (KL/2)] \qquad (1)$$

Rational use of this equation, of which Figs. 2 and 3 are non-dimensional graphical representations, depends on understanding the behavior of eccentricity, which is involved in the grouping ec/r^2, hereafter called γ.

Such understanding is enhanced by study of expressions for "terminal slope," Θ_T, Fig. 1, an angle which is related to eccentricity, is easily measured, and has qualitatively predictable behavior.

Such study supplies further information about end-fixity produced in flat-end tests (one of the items discussed by H. W. Barlow in a recent paper[2]), and it tends to clarify conclusions, stated in a previous paper by the author,[1] to the effect that "effective eccentricity of loading assumes an average value of $0.1r^2/c$ and a maximum value of $0.2r^2/c$."

SLOPE—ECCENTRICITY RELATIONS

The terminal slope expressions alluded to are derived from the load diagram of Fig. 1, by integrating the bending moment equation and applying the appropriate boundary conditions. Equality of end slopes is assumed. Experiments show this assumption to be valid for flat-end columns at or near failing loads. The resulting equations are:

$$\Theta_T = e[K \tan (KL/2)] = e[(2/L)(KL/2) \tan (KL/2)] \qquad (2)$$

$$= \gamma[(r/c)(\sqrt{P/EA}) \tan (KL/2)] \qquad (2a)$$

$$\Theta_T = e_1[2K \sin (KL/4)] = e_1[(4/L)(KL/2) \sin (KL/4)] \qquad (3)$$

$$= \gamma_1[2(r/c)(\sqrt{P/EA}) \sin (KL/4)] \qquad (3a)$$

Discussion will be restricted to the cases of flat-end and pin-end loadings.

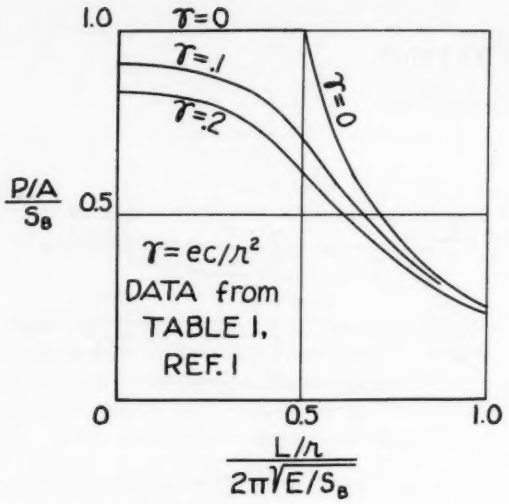

FIG. 2. Unit load versus slenderness ratio for constant maximum stress at point B in Fig. 1.

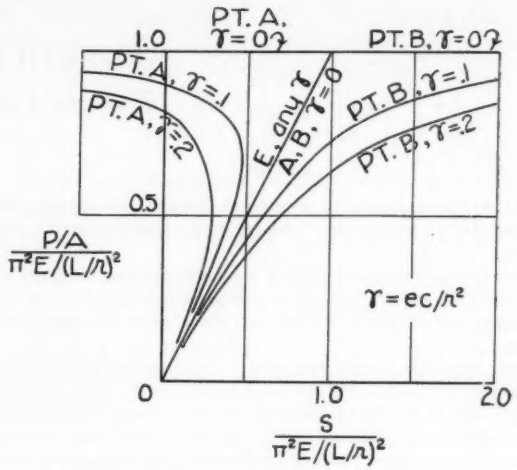

FIG. 3. Unit load versus maximum stress, for constant slenderness ratio, points A, B, E in Fig. 1.

FLAT-END LOADING

Recognizing that the material supporting the column, and the column material itself at the ends, are not perfectly rigid, it is evident that Θ_T, although restricted to a small maximum value, is a function of $KL/2$. (Experiments indicate this relationship to be nearly linear.) In Eq. (2), suppose $KL/2$ to be increased from zero by increasing the load. Careful scrutiny will show that "e" will become smaller, so that the load resultant, P, Fig. 1, will move downward, crossing the X-axis when $KL/2 = \pi/2$.

As $KL/2$ continues to increase (it will not exceed π unless the elastic curve of the column assumes an S-shape), the load condition will be as shown in Fig. 1*b*. Normally, failure will impend when $KL/2$ is such that the compressive stress at point B reaches the elastic limit for the material involved. If, however, at a lower value of $KL/2$, incipient tension occurs at F and F', the column will pivot about D and D', causing a type of premature failure sometimes observed in the testing machine.

Evidently, then, for the column as a whole, γ varies widely with $KL/2$.

Consider, however, the so-called "equivalent pin-end column," Fig. 1*c*. For this, Eq. (3) shows that the eccentricity, e_1, is always positive, decreases as $KL/2$ increases, and never becomes zero. Further, for this component column, Eq. (3*a*) indicates that its value of γ, called γ_1, tends to achieve a uniform value *at failing loads*, regardless of material, slenderness ratio, or unit load at failure. The analysis in support of this statement follows:

First, recalling that as an angle increases from $\pi/3$ to $\pi/2$ its secant increases from 2 to infinity while its sine increases only from 0.866 to unity, Eq. (1) shows that the component column must have a very low slenderness ratio to fail at a value of $KL_1/2$, or $KL/4$, less than $\pi/3$, and hence, for failing loads, the variation of sin $(KL/4)$ in Eq. (5) is bound to be small. At failing loads, then, one would expect γ_1 to be essentially independent of $KL/4$. Since the length term does not appear elsewhere in Eq. (3*a*), it is seen that, for flat-end failing loads, γ_1, and hence eccentricity in the component column, is nearly independent of length. As to eccentricity resulting from slight initial lack of straightness, often associated with the length, the inference is that while such eccentricity would be a factor in determining the direction of deflection, it would not influence the maximum value of Θ_T, which, through Eq. (3*a*), governs γ_1 and the failing load.

Second, assuming reasonably constant elasticity of material supporting the column at the ends, an increase of r/c (shape factor) alone, or of P alone, should cause an increase in Θ_T, while an increase in E alone, or in A alone, should cause a decrease in Θ_T. Inspection of Eq. (3*a*) shows, then, the tendency for γ_1 to remain constant, for failing loads, no matter what quantity in the equation is varied.

But why, at failing loads, should γ_1 assume the *particular* average value of 0.1? To answer this, further experimental investigation of Θ_T behavior, use of the techniques of photo-elasticity, and application of localized stress theory, might prove effective. Meanwhile, the value of γ_1, at failing loads, appears to be known and available for use.

PIN-END LOADING

Consider a column which appears to be subjected to pin-end loading. The end eccentricities, small in magnitude, may be unequal—even opposite in sign. A given end load may not lie on either principal axis of the cross-section. Initially, the member may not be perfectly straight.

However, defining "effective eccentricity" as the value of e in Fig. 1*a* which would lead to the same failing load as that produced by the actual situation, one can reason that if such e were large enough to be easily detected by the unaided eye it is likely that the irregularities in the actual situation would be severe enough so that the column would not be diagnosed as being of "pin-end" classification.

As a rough approach, then, consider the magnitude of e associated with $\gamma = 0.1$. Since the value of r/c for a typical cross-section is about 2/3, e, for $\gamma = 0.1$, would be $0.1r^2/c = 0.1(r/c)^2(c)$, or roughly 4 per cent of c. Now even if c were as little as one inch, this would be visible to the unaided eye; and this crude reasoning, supplementing the results of tests, seems adequate to justify the use of $\gamma = 0.1$ as a conservative round number in dealing with pin-end columns.

Values of γ to Use with Fig. 2

In using Fig. 2 for investigation or design purposes, it is clear that S_B is usually the compressive elastic limit stress for the material. The only doubtful substitutions remaining are those for L and γ. Based on the preceding discussion, the following recommendations are believed to be *conservative* for the common case of primary failure by translation:

1. For columns approaching the pin-end condition, use the full length of the column for L, with $\gamma = 0.1$.

2. For columns approaching the flat-end condition, use *half* the full length of the column for L, with $\gamma = 0.2$.

References

[1] Merriam, K. G., *Dimensionless Coefficients Applied to the Solution of Column Problems*, Journal of the Aeronautical Sciences, Vol. 7, No. 11, page 478, September, 1940.

[2] Barlow, H. W., *The Column Strength of Closed, Thin-Walled Sections of 18–8 Stainless Steel*, Journal of the Aeronautical Sciences, Vol. 8, No. 4, page 155, February, 1941.

A New Instrument for Celestial Navigation

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University of Kansas

ABSTRACT

An instrument is described in which a pair of mirrors and a prism deflect the light of two particular stars into a telescope in such a manner that, when the images of the two are seen superposed in the center of the field of view, the telescope axis must be pointing directly at the celestial pole. Its angular elevation is then equivalent to the latitude, and the rotational position of the mirror combination about the telescope axis shows the sidereal time. The direction of gravity may be indicated either by a bubble cell or by a pendulum stabilized in some manner. A preliminary model, making use of a bubble, has given a probable error of one setting of about 0°.1 in both latitude and longitude, successive readings being separated by less than two minutes of time.

INTRODUCTION

VARIOUS improvements have been made in recent years, and are still being made, in instruments for use in celestial navigation. All of these which have come to the author's notice, however, involve improvements in methods for determining the altitude of a heavenly body. Desirable as such improvements may be, they nevertheless leave the navigator with the necessity of determining his latitude and local time by some sort of tabular or graphical solution. The present paper is to suggest a type of instrument which would eliminate all this work, since both latitude and sidereal time would be read directly from dials after a single setting on the sky. In its simplest form, the instrument would be restricted to night observations, since the use of two fixed stars is required.

FIG. 1. Spherical triangle connecting two stars and celestial pole.

DESCRIPTION OF INSTRUMENT

In describing the instrument two particular stars will be assumed, Polaris and Vega. Fig. 1 represents the triangle on the sky connecting these stars and the true pole. The problem is to cause the light from both stars to appear to come from the pole. This might be done by a separate pair of mirrors for each star, but the testing and adjustment would be much more delicate than with the plan recommended.

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* Associate Professor of Astronomy.

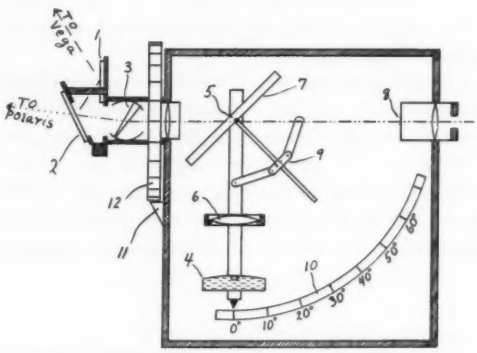


FIG. 2. Vertical section through complete instrument showing positions of mirrors, prism, telescope lenses and leveling element.

This plan is to first superpose the light of the two stars by a pair of mirrors, (*1*) and (*2*), the latter being half-silvered as in a common marine sextant. These are shown at the extreme left of Fig. 2. The angle between the mirrors is permanently set at one-half that between the two stars. Then, when the observer looks through the half-silvered glass toward Polaris, rotation of the pair about the line of sight will cause the image of Vega to swing through that of Polaris. Moreover, when the mirrors are in that position in which the stars are seen superposed, the plane normal to both mirrors (the plane of the figure) is coincident with great circle, *a*, in Fig. 1.

The combined ray of light from the two stars then passes through a small angled prism (*3*), by which it is deviated 61′, the angle (in 1941) between Polaris and the true pole. The plane of this portion of the figure is normal to the apex of the prism, and, when properly oriented in use, is coincident with great circle *b* in Fig. 1. Hence the angle between the portions of Fig. 2 representing the mirrors and the prism should equal the angle at Polaris in the triangle of Fig. 1, at present 72°.2. Of course the mirror portion must be rotated in the proper direction with respect to the prism. In this position the two are clamped rigidly and semi-permanently together to form what will hereafter be referred to as the "head." This is arranged so that it can rotate as a unit about the telescope axis just in front of the objective lens. Then, in view of the above discussion, when the head is so turned that images of both stars are seen in the center of the field of view, it is known that the telescope must be directed at the celestial pole. One erroneous setting could result if

the telescope were directed to a point 61′ from Vega, but this error could never occur in practice.

The telescope is contained in the casing which also holds the leveling element. A vertical central section is shown through this portion of the instrument as it is embodied in the author's present model. The bubble-cell (*4*) with a spherical upper surface is fixed in a frame which turns about shaft (*5*). The axis of this shaft intersects the telescope axis at right angles, perpendicular to the plane of the figure. Lens (*6*) and half-silvered mirror (*7*) produce an image of the bubble at (*8*) where there are cross hairs at the common focus of the telescope objective and eye-lens. The mirror turns independently about the shaft through one-half the angle through which the level-frame turns, so that it is always in position to reflect the center of the bubble cell into the center of the eye-lens. This is accomplished by means of the slidable bearing (*9*) which moves along the rod fixed to the mirror support at its point of rotation, though the result might equally well be achieved with gears. When the bubble-cell is properly adjusted so that a plane tangent to the middle of the spherical surface is parallel to shaft (*5*), then the appearance of the bubble in the center of the field of view indicates that the shaft is horizontal and that the level-frame is vertical. Accordingly, if the telescope has been directed toward the pole by means of the head as previously described, the altitude of the pole (latitude) may be read directly from scale (*10*) by means of the pointer which turns with the level-frame, but on the outside of the casing. Further, since the shaft is known to be level, the plane of the figure must coincide with the plane of the celestial meridian, and hence an index, such as (*11*), fixed to the casing, may indicate the sidereal time on a graduated scale (*12*) which rotates with the head. Presumably a finished instrument would have vernier adjustments for both latitude and sidereal time, so that the settings could be made accurately and conveniently and the readings taken quickly.

Operation

To operate the instrument, the observer first brings the head to the approximately correct position from the obvious direction of Vega in the sky. Polaris is then located in the field of view and the level-frame is brought to such a position that, when the instrument is bodily "rocked" about the line of sight as an axis, the images of the center of the bubble and of Polaris move to intersect each other at the center of the field.

The head is then rotated to bring Vega into view, and rotation is continued until, as the instrument is rocked, Vega and the bubble pass over Polaris simultaneously, also at the center of the field. This will probably necessitate a second adjustment of the latitude setting, which may, in turn, necessitate slight readjustment of the head. This second approximation should be sufficient, however, and the latitude and sidereal time are then read directly from the appropriate dials. It should be emphasized that the two adjustments may be made one at a time, not necessarily simultaneously, for this greatly simplifies the operation.

A further decided simplification of operation may be brought about by properly adjusting the sensitivity of the bubble to the focal length of the telescope objective. When this is done, if Polaris is brought into coincidence with the bubble in the center of the field of view, the two will remain in coincidence even though the telescope is tilted up or down so that they no longer appear in the center. Thus it is only necessary that the coincidence of the two stars and bubble be brought about somewhere on the vertical line through the center of the field. Unfortunately this advantage cannot apply also to a sidewise tilt of the casing.

The instrument is naturally a little more difficult to operate than a bubble sextant, since, in the form described above, three images must be superposed rather than two. Nevertheless it has been found possible with the author's homemade model to make successive independent readings separated by an interval of less than two minutes. It is certain that this time will be materially reduced with a smaller and lighter model which can be more conveniently manipulated. The accuracy obtained with the present model is also encouraging, the probable error of a single setting being only slightly over 0°.1 in both latitude and time. The size of these errors is due at least in part to the fact that the readings are being made directly, without benefit of vernier, from scales of only 3 and 4 inches radius.

This instrument, just as any other which depends upon the effective direction of gravity, will have errors introduced by the horizontal components of the various accelerations to which an aeroplane is subjected. However, there seems to be no reason why the resulting error in position should be any greater than with the other types, though, as with them, the difficulty of operation may be somewhat increased. The present model has not been tried out in the air, and hence it is impossible to predict the extent to which this additional difficulty of operation under flying conditions will be compensated by the increased convenience and accuracy expected in a finished instrument.

Use of Other Stars

The use of an index star at some distance from the pole is necessary for accuracy in the time determination, but any one star like Vega can then be used only during certain hours of sidereal time. It is therefore necessary to have four or five index stars available—bright stars at unique distances from Polaris to guard against mistaken identity. A pair of mirrors must be provided for each such star, designed to superpose it on Polaris. These units would be arranged to clamp interchangeably onto the prism section of the head, pins

being provided to insure correct orientation with respect to the prism.

For regions near the equator and for the entire southern hemisphere another polar star will be needed, and this will require another prism unit giving a deviation appropriate to the star selected. Theoretically any two stars are satisfactory, but the nearer to the pole one of them is the simpler the operation will be.

Treatment of Atmospheric Refraction

The effect of atmospheric refraction on the sidereal time may be largely avoided by employing an index star as high in the sky as possible, but the effect on the latitude is not so easily avoided. This can be at least reduced, however, by making use of a feature not mentioned heretofore. If the half-silvered mirror (*7*) is to produce an image of the bubble-cell which is stationary in the eye-piece regardless of the position of the level-frame, the reflecting surface of the mirror must be precisely in the rotation axis of shaft (*5*). However, if the reflecting surface is displaced a calculated amount toward the eye-piece, the bubble-cell will appear to be displaced in the field of view in such a direction as to partially compensate for atmospheric refraction. This displacement of the mirror would be necessary to some extent anyway, since the converging beam of star light from the telescope objective is displaced varying amounts in passing through mirror (*7*) in its different positions.

Testing and Adjustment

The adjustments in the head of the instrument are not at all critical, for any errors likely to occur in a well constructed instrument resolve themselves almost completely into index errors which may be easily tested and removed. The mirrors are in satisfactory adjustment as long as the index star can be superposed on Polaris, and the prism used in the author's preliminary model would have to be rotated a whole degree before the total deviation would be changed by as much as one minute. With Polaris an error of a degree or less in the angle between mirror and prism units may be handled as an index error on the sidereal time scale. However, if mirror combinations for different index stars are to be used interchangeably, they must all fit onto the prism so as to produce the same index error; hence the need for pins to insure proper orientation. The index settings of both scales should be tested from time to time by making observations from the ground at a known latitude and sidereal time.

After an interval of three years or so a slight correction will be necessary due to the "precession of the equinoxes," which shifts the position of the pole among the stars. This affects the instrument in three ways, all of which are easily corrected. First, it changes the angle from Polaris to the pole, corrected by changing the angle of incidence on the prism. Second, it changes the angle between circles *a* and *b* in Fig. 1, corrected by rotating the mirror unit on the prism unit. Finally, there is a gradual change in the right ascensions of the stars, which introduces a slight index errror on the sidereal time scale.

Two matters are important in connection with the leveling element as it has been described, but these should not get appreciably out of adjustment in a well constructed instrument. The shaft (*5*) must intersect and be perpendicular to the telescope axis, and the bubble-cell must be so adjusted that, when the bubble is seen in the center of the field, the shaft is level. Errors in either of these adjustments may be detected through the fact that they produce errors in the time reading which vary with the latitude, but another test has been developed which can be carried out at one station.

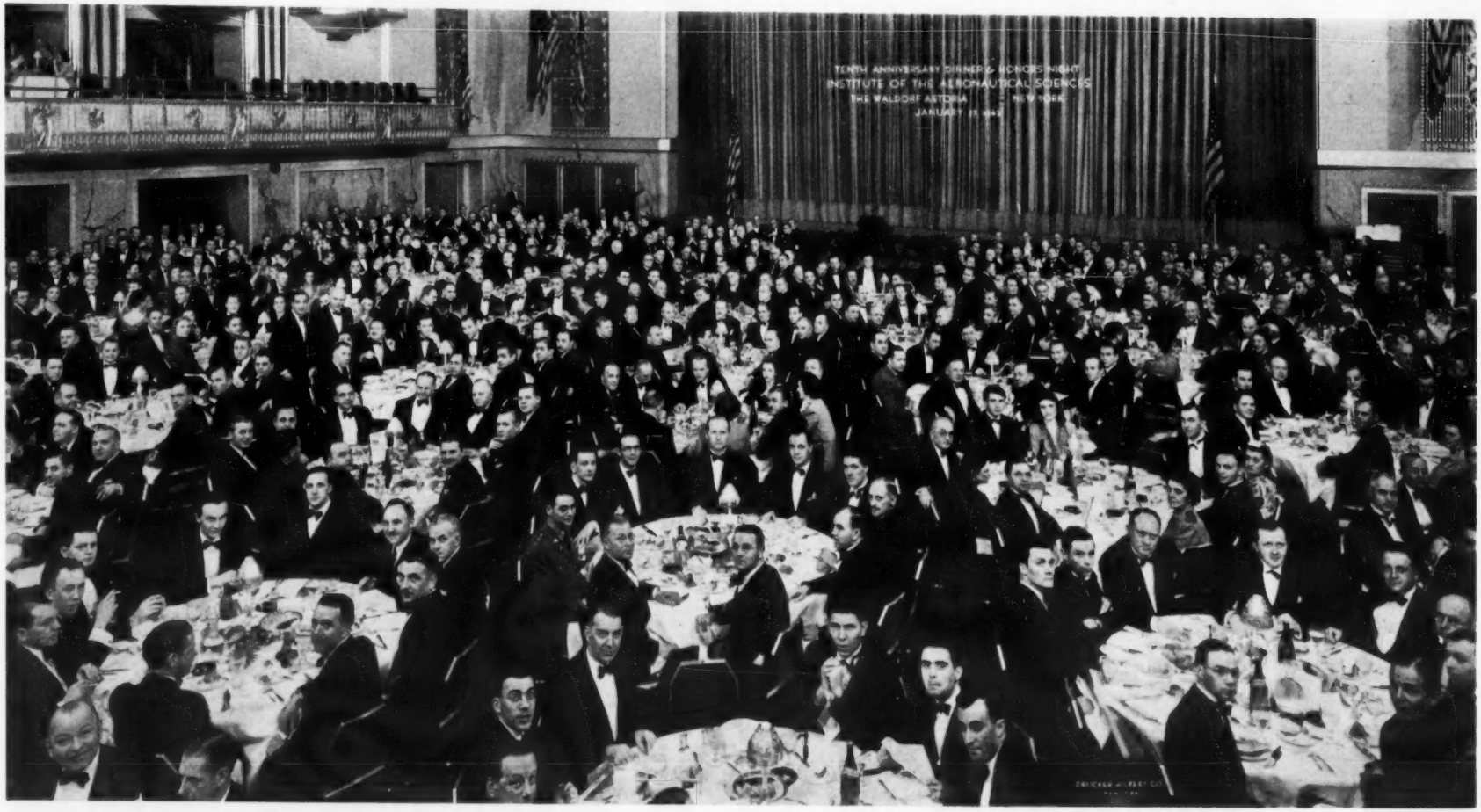
Additional Features

It should be pointed out that if the head is completely removed the instrument can be used to observe directly the altitude of any celestial object, this being read from the latitude scale. This would make it unnecessary to have a second complete instrument for use in the daytime.

Finally, a theoretical possibility may be mentioned, though it may be doubted that this would ever be practicable. If a chronometer keeping Greenwich sidereal time were built into the instrument in such a way as to move the sidereal time index around, the time dial could be arranged to read directly the longitude of the observer.

Conclusion

The main advantage claimed for the instrument is speed, since, for night observations, all computation and all reference to tables or charts are eliminated. The preliminary model has given very encouraging results, and further developments are in progress.



Honors Night and Tenth Anniversary Dinner, Institute of the Aeronautical Sciences, Hotel Waldorf-Astoria, New York, January 27, 1942

Institute of the Aeronautical Sciences Honors Night and Tenth Anniversary Dinner

THE Honors Night Dinner, marking the tenth anniversary of the Institute, was held on Tuesday, January 27, 1942, in the Grand Ballroom of the Waldorf-Astoria in New York. Eight hundred members and guests of the Institute attended this annual presentation of awards and honors.

The retiring President of the Institute, Frank W. Caldwell, Director of Research, United Aircraft Corporation, acted as Toastmaster. The program opened with the National Anthem, followed by the President's greeting to members and guests. Excerpts from the speeches of presentation and acceptance of awards follow. Citations for the awards are shown on the accompanying reproductions of the certificates.

GREETING BY THE PRESIDENT OF THE INSTITUTE:

PRESIDENT CALDWELL: Welcome to the Tenth Anniversary Dinner of the Institute of the Aeronautical Sciences. I hope this Honors Night will be worthy of such an eventful occasion.

The Institute has been greatly honored by receiving a letter from the President of the United States which I take pleasure in reading to you.

(President Caldwell read the letter which is reproduced on the opposite page.)

For President Roosevelt to take time in these eventful days to address scientific workers in aeronautics through the Institute is an indication of the importance he places on their accomplishments. In our reply we will assure our Commander-in-Chief that every member of the Institute engaged in aeronautical development will respond to his call to the limit of his ability and energy. Our Tenth Anniversary has been made notable by these felicitations.

In the interest of a streamlined dinner, I shall make my introductory remarks as brief as possible. All of our lives today are dominated by the single purpose of winning the bitter struggle ahead of us. During these dark days our unity will be even more complete and our objectives more clear. We are a young and vigorous nation. As Americans, we shall carry out our appointed task against the enemy with confidence and determination. As engineers, we shall continue our struggle with the forces of nature with infinite patience. There is no group anywhere in the civilian effort with a greater opportunity to serve the country. I predict that our performance will be adequate.

THE DANIEL GUGGENHEIM MEDAL FOR 1941

Awarded by the Daniel Guggenheim Medal Board, composed of representatives of the American Society of Mechanical Engineers, the Society of Automotive Engineers, the Institute of the Aeronautical Sciences and previous recipients of the medal. Elmer A. Sperry, Jr., is Chairman of the Board.

Presentation made by Brigadier General Donald H. Connolly, Military Director of Civil Aviation, Army Air Forces, to Juan T. Trippe, President, Pan American Airways System.

PRESIDENT CALDWELL: The Institute was asked by the Daniel Guggenheim Medal Board to include in its Honors Night program the presentation of a great award. I take pleasure in turning this part of the program over to Mr. Elmer A. Sperry, Chairman of the Medal Board.

MR. SPERRY: The Daniel Guggenheim Medal is the highest award that an American can receive for a life of achievement in aeronautics. Those who have been honored have been the outstanding men in our aeronautical history.

Tonight we are honoring another great pioneer. We have asked an officer with a distinguished career in the United States Army to make the presentation. You will remember him as an administrator of the C.A.A. He continued his fine record and now is the Military Director of Civil Aviation of the Army Air Forces and is coordinating civilian and military air transport—Brigadier General Donald H. Connolly.

GENERAL CONNOLLY: The recipients of the Guggenheim Medal, starting with Orville Wright, have been in a large degree the human milestones in man's progress in the conquest of the air. Most of the twelve previous recipients of this award have been scientists who solved specific problems of aircraft and engine design looking toward improved performance. In fewer instances, they have been engineers who produced revolutionary or superior types of commercial aircraft.

Brig. Gen. Donald H. Connolly (right) congratulates Juan T. Trippe on receiving The Daniel Guggenheim Medal for 1941

Now, for the first time, the award is given to a man whose achievements lie principally in the field of operations. That fact seems very significant. It does not mean that the opportunities for scientific development are in any sense narrower than they have been or that the improvements in aircraft will be any less rapid in the future, but it does mean that our best transport aircraft have reached such a point of reliability that the need for technical improvement no longer dwarfs all other considerations. In other words, the engineers and technicians have done their job so well that they now must admit into aviation's "Hall of Fame" a man whose achievements are mainly operational.

THE WHITE HOUSE
WASHINGTON

January 23, 1942

My dear Mr. Caldwell:

The tenth anniversary of the Institute of the Aeronautical Sciences, to be observed on January twenty-seventh, comes at a time when achievements in aeronautical science are of the most far reaching importance to our war effort.

In research laboratories of the Government and of industry, as well as in the laboratories of private scientific and educational institutions, the talent of America is being marshaled in a united effort necessary to develop for our armed forces aircraft of greater performance and effectiveness than those of our enemies.

Thus is the foundation laid for achieving supremacy in the air. Our country is engaged in a great war in which, more forcibly than ever before in history, the challenge comes to men of science to devote all of their energies to the supreme objective of winning the war.

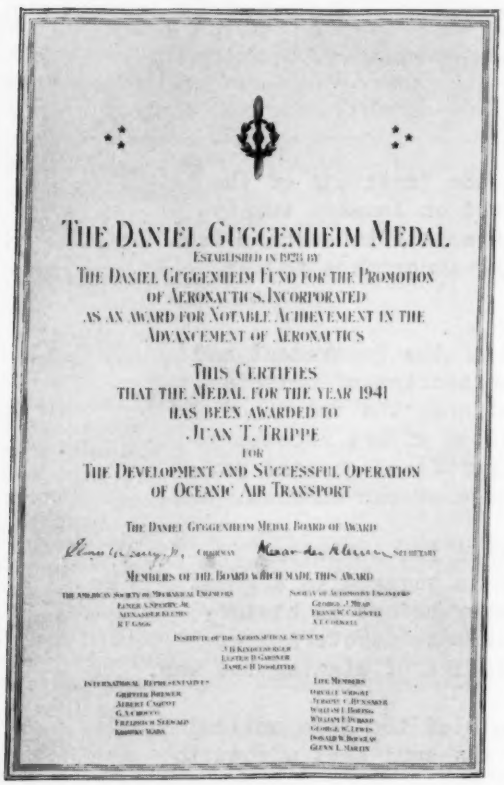
I felicitate the Institute of the Aeronautical Sciences on its tenth anniversary and send best wishes to all the members.

Very sincerely yours,

Franklin D. Roosevelt

Mr. Frank W. Caldwell,
President,
Institute of the Aeronautical Sciences,
1505 RCA Building, West,
30 Rockefeller Plaza,
New York, N. Y.

Of course, it is impossible to build a wall between the developer of a great commercial airline operation and the designer of the aircraft to fly it. This is particularly true in tonight's case, which involved the pioneering of overwater routes. There is no doubt that Juan T. Trippe, fighting year after year for safer and more efficient overwater operations, has had a profound influence on the design of big flying boats. Moreover, it is also possible that the flying clippers of today seem more reliable than they might in the hands of a less capable operator. By that I mean that the



THE DANIEL GUGGENHEIM MEDAL

ESTABLISHED IN 1928 BY
THE DANIEL GUGGENHEIM FUND FOR THE PROMOTION
OF AERONAUTICS, INCORPORATED
AS AN AWARD FOR NOTABLE ACHIEVEMENT IN THE
ADVANCEMENT OF AERONAUTICS

THIS CERTIFIES
THAT THE MEDAL FOR THE YEAR 1941
HAS BEEN AWARDED TO
JUAN T. TRIPPE
FOR
THE DEVELOPMENT AND SUCCESSFUL OPERATION
OF OCEANIC AIR TRANSPORT

THE DANIEL GUGGENHEIM MEDAL BOARD OF AWARD

MEMBERS OF THE BOARD WHICH MADE THIS AWARD

soundness of an airplane cannot alone make for safe airline operation. Endless patience and constant administrative vigilance are prime factors in any safety record.

I do not think that the way to tell the story of Juan Trippe or his organization is with dry statistics. It is much simpler to say that wherever on the broad surface of the world an American Flag Airline has been deemed important to this nation, Juan Trippe has been prepared to operate it superlatively well.

Down the long southern reaches of this hemisphere and across both oceans the men of Pan American Airways have hacked facilities out of mountain and jungle or built them from scratch on remote island outposts. Back and forth they have flight tested each new route with painstaking care before it began operation. The responsibility for this job has been squarely up to the man we are honoring here tonight.

Juan Trippe, I have said very little about you personally. Despite a physical handicap, you fought your way into naval aviation during the First World War. For the last fifteen years you have fought with brains and skill to keep this nation in the international race for commercial air supremacy. Now, in the Second World War, your great organization is doing yeoman service in the great overwater transport problems we now face.

I present to you the Daniel Guggenheim Medal for 1941 "for the development and successful operation of oceanic air transport."

MR. TRIPPE: The inauguration and operation of overseas air transport was a community job in every sense of the word. I refer not only to the personnel, the men and women of the Pan American Airways organization, but to those of other organizations who had such a large part in bringing this about.

I refer to the Sikorsky Company, to the Martin Company, to the Boeing Company, whose ships have made possible these ocean services, and to the engine and propeller manufacturers whose progressive development also contributed greatly to making it possible for our organization and Pan American to have done this job.

In the Pan American organization itself there are many thousands who had a direct part in the job, starting with the Board of Directors who had the guts and the vision to be willing to underwrite, back there in 1933, a large financial commitment that made possible the undertaking of this ocean service. I refer to the men in the Caribbean who undertook the first technical research to bring this about, who operated the first four-motored plane, who developed the multiple flight crew, who undertook studies of celestial navigation and who developed the long-range direction finder and other radio aids that have made long distance transport possible.

I refer to the men who made the field surveys, who went to Iceland, to Greenland, to Labrador, to the Azores, and to ports in Africa; some of whom spent the winter on the icecap in Greenland and gave their lives in order to collect data that made it possible to determine what were the best routes in those days in which work should be concentrated—data which, I am happy to say, has been useful to our own Government and to our allies since we entered the war.

I refer to those who pioneered the Pacific airways, who went forward in 1935 to build air bases on Midway Island, Wake Island, Guam and at Manila—Wake Island was then an uninhabited island without harbors, surrounded by breaking surf through which the material had to be brought to erect on the island the necessary buildings.

I refer to the clipper captains and their crews who have done this job, and above all, to Eddie Musick who pioneered the trans-Pacific Service, who went forward in 1935 in an American aircraft, owned and operated by an American company, built in the United States, and in charge of an American captain and an American flight crew who were the first to fly a major ocean route carrying mail and passengers.

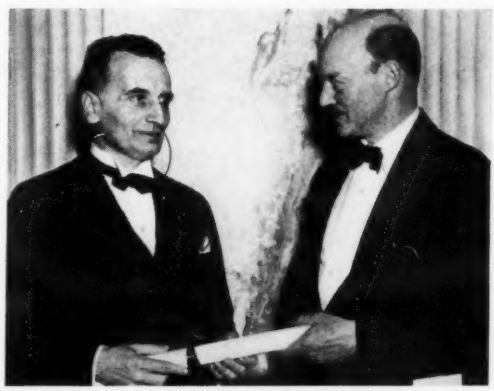
Since then, as you all know, Captain Musick made the great sacrifice in pioneering the route to Australasia, but his fellow captains have carried on and when the war broke out, the Second World War, we found the American Flag Service operating to Europe, to the Orient, to Australasia and placing this country in the first place on the trade routes of the world, just as had their predecessor clipper captains of a hundred years ago in the days of sail.

Since Pearl Harbor, since we entered the war, these same men have carried on at their posts in Midway and Wake and Guam and Manila, Singapore, Hong Kong, in China, Burma, India, Africa and at their posts in Europe, Portugal, Ireland and Great Britain. They and the flight captains are carrying out the assignments that were given to them by the Army and Navy, whether those assignments lead them into combat zones or not. I believe, when the history of this war is written that these men will have written another bright page in the history of American aeronautics, and on behalf of all of them, I am proud to accept this medal.

The Sylvanus Albert Reed Award for 1941

Presented by Dr. J. C. Hunsaker, Chairman, National Advisory Committee for Aeronautics, to Dr. Theodore von Kármán, Director, Daniel Guggenheim School of Aeronautics, California Institute of Technology.

President Caldwell: Our next presentation is the Sylvanus Albert Reed Award. I am happy to participate in honoring the memory of an outstanding pioneer, a scholar, a gentleman, and an old friend. I shall call on the Chairman of the National Advisory Committee for Aeronautics to make this presentation. I do not need to introduce Dr. Hunsaker, first President of the Institute.



Dr. Th. von Kármán (left) accepts The Sylvanus Albert Reed Award for 1941 from Dr. J. C. Hunsaker.

Dr. Hunsaker: The Sylvanus Albert Reed Award is given "For a notable contribution to the aeronautical sciences resulting from experimental or theoretical investigations, the beneficial influence of which on the development of practical aeronautics is apparent."

The Reed Award was established by bequest of the late Dr. Sylvanus Albert Reed to recognize creative work. Recognition was to be tested by widespread use. Hence the citation just quoted for the award to Dr. von Kármán refers to the practical part only of his work. However, I believe it appropriate to mention before this body von Kármán's much wider scientific contributions in the fields of elasticity, plastic failure of materials, equivalent width of reinforced thin sheets, buckling and stability, non-linear deflections, vibration and flutter problems.

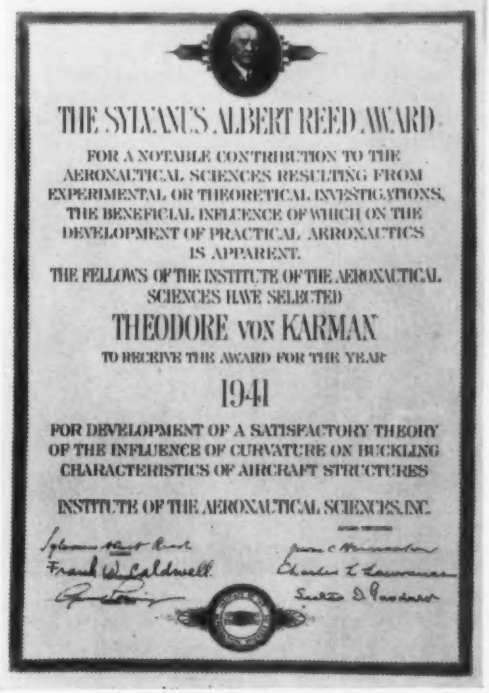
In the field of fluid mechanics, Dr. von Kármán became first known by his classic work on resistance and in particular for the so-called "vortex street." This work on skin friction produced engineering formulas for the prediction of drag which made Prandtl's boundary layer theory of practical use. More recently he has made stimulating suggestions, at least, toward a theory of isotropic turbulence. Dr. von Kármán was a pioneer in applying potential theory to the two-dimensional flow of a perfect fluid past an airfoil. Also recently he has made scientific advances in the theory of supersonic flow and the thermodynamics of the motion. This work is really in advance of the airplanes of today but is in anticipation of the much swifter ones of the future. Dr. von Kármán is a teacher's teacher just as Justice Cardozo was a lawyer's lawyer. The roster of his colleagues and students who have been influenced by his teaching goes literally round the world.

Dr. von Kármán: I want to express my appreciation for this great honor awarded to me by the Institute of the Aeronautical Sciences, and also for the very fine words of my old friend, Jerome Hunsaker. I recall very vividly when I met him first about twenty-two years ago. He came quite a long way to see me and ask me whether or not I knew everything about skin frictions, boundary layer, and turbulence. I believe that after two decades, after twenty-two years, there is nobody who knows everything about these subjects, but his visit gave me some inspiration to find out at least something about them.

I also want to express with due credit my thanks to my two young collaborators, Dr. Tsien and Dr. Dunn, who assisted me in the research work to which this award refers.

I appreciate this award for three reasons. First, this award is given for scientific achievement which is useful to the art of airplane design. Airplane design is, in fact, an art based on science, therefore it requires two kinds of ability. One is inventive ability and the other is analytical ability. The inventive activity is much more in the eye of the public, but this award makes a scientist feel good because he sees that his work also means something.

The second reason is that this award is given by a vote of the Fellows of the Institute. Even the greatest diplomat cannot fix the opinion and the vote of this body which comprises most of the aeronautical talent which is available in this country.


THE SYLVANUS ALBERT REED AWARD

FOR A NOTABLE CONTRIBUTION TO THE AERONAUTICAL SCIENCES RESULTING FROM EXPERIMENTAL OR THEORETICAL INVESTIGATIONS, THE BENEFICIAL INFLUENCE OF WHICH ON THE DEVELOPMENT OF PRACTICAL AERONAUTICS IS APPARENT.

THE FELLOWS OF THE INSTITUTE OF THE AERONAUTICAL SCIENCES HAVE SELECTED

THEODORE VON KARMAN

TO RECEIVE THE AWARD FOR THE YEAR

1941

FOR DEVELOPMENT OF A SATISFACTORY THEORY OF THE INFLUENCE OF CURVATURE ON BUCKLING CHARACTERISTICS OF AIRCRAFT STRUCTURES

INSTITUTE OF THE AERONAUTICAL SCIENCES, INC.

Frank W. Caldwell

My third reason is the following: I was lucky enough to get recognition for my scientific work both abroad and in this country, but most of this recognition went for work that I had been doing before I came to this country at the invitation of the Guggenheim Foundation about fifteen years ago. However, this award refers to research work which has grown out of the needs of American aviation and is based on my experience in America. This gives me encouragement and hope that I shall be able, within the narrow limits which are given to a scientist of my type, to make any small contribution to the great task which the aviation of my adopted country faces in these days of world crisis.

THE OCTAVE CHANUTE AWARD FOR 1941

Presented by T. P. Wright, Assistant Chief of the Aircraft Branch, War Production Board, to Melvin N. Gough, Senior Test Pilot, Langley Memorial Aeronautical Laboratory, National Advisory Committee for Aeronautics.

PRESIDENT CALDWELL: The Institute has established a series of awards in honor of pioneers of aviation. Octave Chanute was one of our earlier American pioneers who contributed much to sound engineering and design of the airplane wing structure. I shall ask one of our Past Presidents to make this presentation.

MR. WRIGHT: Test piloting is one of the most difficult phases of aeronautical engineering. I think that any chief engineer or anyone engaged in government service who has to deal with the actual fixing of the performance characteristics of airplanes will admit that a truly great test pilot is difficult to find.

I think you can count the truly great ones on the fingers of your two hands at this time. It requires an engineer, a person who is familiar with the airplane structure and knows what he is doing when he is in the air from that standpoint. It requires an aerodynamicist, one who knows why the responses to his touch on the stick are what they are. It requires, of course, an excellent pilot, one who handles his plane instinctively. It requires a scientist, one who realizes the fundamentals behind aircraft design; and it also requires, perhaps, one characteristic not frequently appreciated, that of an executive, one who is able to come down and tell just what he has found out about his craft in the air and explain it to the engineers on the ground so that they may make modifications and note what to do before his next flight.

Melvin N. Gough (left) receiving The Octave Chanute Award for 1941 from T. P. Wright.

The Octave Chanute Award is made in memory of one who had these characteristics and who, through his gliding experiments and scientific researches, contributed much toward the progress of aviation. The past recipients of this award, of whom there are two—and one of them is with us tonight—are Edmund T. Allen and Howard Hughes.

The 1941 recipient, Melvin N. Gough, has had a career of flying and scientific working career principally in the National Advisory Committee for Aeronautics, although he received his flying training in the Navy where he is now a Lieutenant in the Naval Reserve. He has written many scientific papers, most of which have appeared as reports of the National Advisory Committee for Aeronautics. He is a Fellow of the Institute.

The Octave Chanute Award is given for a notable contribution made by a pilot to the aeronautical sciences. It is with great pleasure that I present Mr. Gough with this award for his outstanding contributions to fundamental research in aeronautics as conducted on airplanes in actual flight.

The Octave Chanute Award
of the
Institute of the Aeronautical Sciences
for a notable contribution made by a
pilot to the aeronautical sciences
is awarded to
Melvin Neilson Gough
for the year 1941
for his outstanding contributions to
fundamental research in aeronautics as
conducted on airplanes in actual flight.

Committee of Award

Frank W. Caldwell
President

Lester D. Gardner
Executive Vice President

MR. GOUGH: It is difficult for me to tell you how happy I am to receive this highest award in my profession. I am happy to be associated with those who have received the award before me. I am also happy that the Institute sees fit to recognize a profession as it does mine.

In accepting the award personally, I must tell you that it would not have been possible without the very close guidance and fostering on the part of the administrative staff of the N.A.C.A. and without the equipment which they have available and the very close cooperation of their engineering staff.

THE LAWRENCE SPERRY AWARD FOR 1941

Presented by Charles H. Colvin, Director, Daniel Guggenheim School of Aeronautics, New York University, to Ernest G. Stout, Engineer in charge of Aerodynamics and Flight Test, Consolidated Aircraft Corporation.

PRESIDENT CALDWELL: A pioneer of a somewhat later period was Lawrence Sperry. While he belonged truly to the pioneer period, aviation has developed so rapidly that many of us here remember him as a collaborator and friend. All of us know about his contribution to the art. We have asked the Director of the Daniel Guggenheim School of Aeronautics, New York University, to present the Lawrence Sperry Award.

MR. COLVIN: As you have seen from your program, the Lawrence Sperry Award was established and endowed six years

ago by the brothers and sister of Lawrence Sperry. The recipient for the year 1941 has been chosen by the Board of Award whose members are Lt. Col. James H. Doolittle, Lester D. Gardner, Charles L. Lawrance, Grover Loening, Glenn L. Martin and Elmer A. Sperry, Jr.

Charles H. Colvin (left) presenting The Lawrence Sperry Award for 1941 to Ernest G. Stout.

The Award is made for "a notable contribution by a young man to the advancement of aeronautics." The Board has selected as the notable contribution in 1941 the work on the experimental determination of the hydrodynamic stability of model flying boats and seaplanes by Ernest Gordon Stout.

THE LAWRENCE SPERRY AWARD
FOR A NOTABLE CONTRIBUTION MADE BY A YOUNG MAN TO THE ADVANCEMENT OF AERONAUTICS
THE BOARD OF AWARD HAS SELECTED
ERNEST GORDON STOUT
TO RECEIVE THE AWARD FOR THE YEAR 1941
FOR HIS CONTRIBUTIONS TO THE EXPERIMENTAL DETERMINATION OF HYDRODYNAMIC STABILITY OF MODEL FLYING BOATS AND SEAPLANES
BOARD OF AWARD
INSTITUTE OF THE AERONAUTICAL SCIENCES

Mr. Stout, who is in charge of aerodynamics and flight testing for Consolidated Aircraft Corporation, has been engaged in these studies of model seaplane and flying boat behavior for more than four years. During that time he has devised several new techniques for simulating full-scale aerodynamic conditions and thereby directly relating the hydrodynamic results to full-scale performance. His work has been of very great value, not only to his own company, but to the Government and to the other builders of large flying boats.

The Lawrence Sperry Award is made not only in recognition of these achievements but in the hope that the recipient and other young aeronautical engineers, as well, may be inspired to do still greater things.

It gives me very great pleasure to present this award for two particular personal reasons: first, I was for some time associated with Lawrence Sperry and that, of course, makes me very glad to be associated with this award; secondly, you are a graduate of our School of Aeronautics at New York University and we at the school are extremely proud of you as an alumnus.

MR. STOUT: I am greatly honored to be the recipient of this award which commemorates a young man who was so outstanding in aviation's progress. I sincerely hope that, in the troubled years before us and in the great era of peaceful progress that will surely follow, I shall be able to fulfill in some measure the obligations and responsibilities of this honor.

I am sure Lawrence Sperry never considered a job as completed. I will be gratified if my work will add some part to the great work that he has pioneered.

THE JOHN JEFFRIES AWARD FOR 1941

Presented by Dr. Louis H. Bauer, Editor, "Journal of Aviation Medicine," to Major Harry G. Armstrong, (M.C.) Director, Research Division, School of Aviation Medicine, Randolph Field.

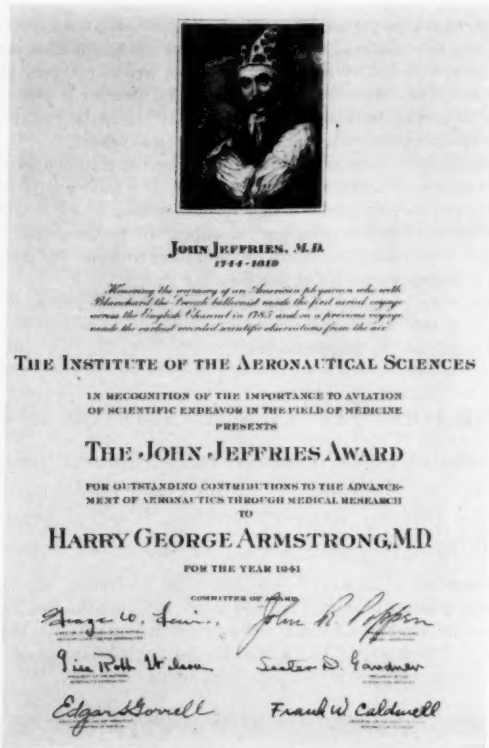
PRESIDENT CALDWELL: An American physician, an aeronautical pioneer of more than 150 years ago, was the first to fly across the English Channel. It is very fitting that we should honor his memory. Dr. Louis H. Bauer, who received the Award last year, will present the John Jeffries Award.

Dr. Louis H. Bauer (left) presenting The John Jeffries Award for 1941 to Major Harry G. Armstrong. Dr. Bauer was the 1940 recipient.

DR. BAUER: To those of us who have long been interested in aviation medicine, the recognition given to it by the Institute of the Aeronautical Sciences is a source of much gratification. The establishment of the John Jeffries Award last year by the Institute gave us an official recognition, not by the medical profession, which might be expected to acknowledge it, but by scientists interested in other phases of aviation, who have come to realize the value of aviation medicine to their own special work.

Aviation medicine has come a long distance since its birth during the First World War. It had to fight for acceptance then

and for some years afterward. Now it is generally accepted as an essential part of the great field of aeronautics. The work that has been done on the physical requirements of the flyer, on the effects of altitude, the effects of high speed, and on oxygen supply—to mention but a few of the research projects—is tremendous.


JOHN JEFFRIES, M.D.
1744-1819
Honoring the memory of an American physician who with Blanchard the French balloonist made the first aerial voyage across the English Channel in 1785 and on a previous voyage made the earliest recorded scientific observations from the air
THE INSTITUTE OF THE AERONAUTICAL SCIENCES
IN RECOGNITION OF THE IMPORTANCE TO AVIATION OF SCIENTIFIC ENDEAVOR IN THE FIELD OF MEDICINE PRESENTS
THE JOHN JEFFRIES AWARD
FOR OUTSTANDING CONTRIBUTIONS TO THE ADVANCEMENT OF AERONAUTICS THROUGH MEDICAL RESEARCH TO
HARRY GEORGE ARMSTRONG, M.D.
FOR THE YEAR 1941
COMMITTEE OF AWARD
Gill Robb Wilson
Lester D. Gardner
Edgar S. Gorrell
Frank W. Caldwell

During the last war it was a case of finding a plane equal to the capabilities of the pilot. Now it is a case of finding a pilot who can keep up to the plane. The tremendous strides in aeronautical engineering have kept the medical profession on the constant alert to keep pace with engineering advancement and provide a pilot who can stand up physically to the demands of the plane and to protect him against the forces of nature. For example, during the last war, altitude flying, which was rarely carried out over 20,000 feet, was a matter of oxygen supply. Now, with military planes operating at 30,000 to 40,000 feet, we have to deal with the additional effects of reduced barometric pressure and the prevention and treatment of aero-embolism. It was not until after the last war that any plane reached the speed of 200 miles an hour, and that was in a racing plane, not a military one. Now dive-bombing planes reach a speed of 500 miles an hour before they pull out, throwing an enormous strain on the human make-up.

In my opinion, the Committee this year could have chosen none other than the man it did choose. While all the acclaim possible should come to the recipient, I feel that acclaim should also go to the Committee for their wise selection. The Committee consisted of Dr. G. W. Lewis, Director of Research of the National Advisory Committee for Aeronautics; Gill Robb Wilson, President of the National Aeronautic Association; Edgar S. Gorrell, President of the Air Transport Association of America; Capt. J. R. Poppen, U.S.N., President of the Aero Medical Association; Frank W. Caldwell, President of the Institute of the Aeronautical Sciences; and Lester D. Gardner, President of the Aeronautical Archives of the Institute.

There has been no one in recent years who has contributed so much to aviation medicine as has this year's recipient. An officer of the Army Medical Corps, he has by his research and writings, advanced our knowledge in all phases of aviation medicine. His contributions to the effects of extreme altitudes and our knowledge of aero-embolism; his work on aero-neurosis and on the effects of high speed have been outstanding. His book on the "Principles and Practice of Aviation Medicine" is the pre-eminent work on the subject today. His co-authorship with Colonel Grow of the book "Fit to Fly" has given the pilot the practical side of aviation medicine which he should know for his own protection. He has been largely responsible for the growth and importance of the Aero Medical Research Laboratory. Now in his new task of organizing and operating the Research Division of the School of Aviation Medicine, I venture to predict that he will play a large part in solving other medical problems of flying to which we do not yet have the answer.

His training, his career as a flight surgeon and research worker in aviation medicine, and his recent trip to England where he familiarized himself with war problems first hand make him the outstanding man for the position which he now occupies. I know he will bring further credit, not only to himself, but to the Army.

The John Jeffries Award was established last year by the Institute in memory of Dr. John Jeffries, an American physician who made the first known scientific observations in the air. It is given annually to a physician who has contributed to the advancement of aeronautics through medical research. I present this award in the name of the Institute for the year 1941 to Major Harry G. Armstrong, Medical Corps, United States Army.

MAJOR ARMSTRONG: It is indeed a great honor to receive this award. I receive it with a great deal of humility because I know, perhaps better than anyone else, that I merely represent an organization of individuals who have contributed to our knowledge in aviation medicine.

As far back as 1930 the Air Corps began to show an interest in the medical side of flying. To my knowledge the United States Army Air Corps was the first to sponsor extensive research in aviation medicine since the last war. Therefore, a great deal of credit must be given to those people in the Air Corps who had the foresight and the forethought to sponsor something in an allied science which we hope will pay big dividends today.

I would also like to mention those enlisted men of the Army Medical Department who did a great deal in solving many of our unknown problems, who exposed themselves to unknown conditions in which there was not only a hazard involved but a hazard that was unknown.

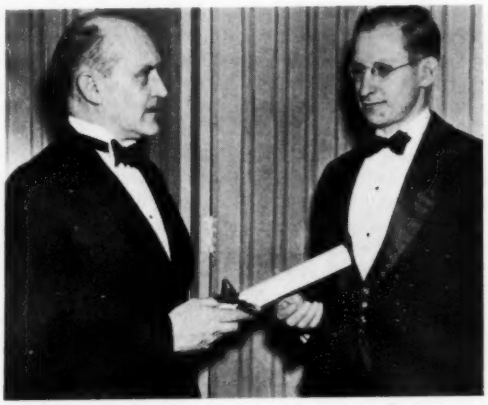
As far as we know, we are as well advanced in this field as any country in the world. Insofar as the fitness of our pilots, their selection and their protection against high speed, high altitude, cold, and high accelerations are concerned, I am happy to say that I firmly believe that in that respect we need fear no other country, no matter who they may be.

THE ROBERT M. LOSEY AWARD FOR 1941

Presented by F. W. Reichelderfer, Chief of the U.S. Weather Bureau, to Dr. Horace R. Byers, Associate Professor, Institute of Meteorology, University of Chicago.

PRESIDENT CALDWELL: In time of war nobody talks about the weather, but we seem to have some scientists who are doing something about it. Our next award honors the memory of a meteorologist who was the first casualty of the present world conflict. The Chief of the Weather Bureau will present the Robert M. Losey Award.

MR. REICHELDERFER: It is quite true that in these days of war restriction one cannot be sure but that his loyalty may be questioned if he mentions the weather above a whisper, let alone mentions it in public. The war's influence, felt in nearly every field of human endeavor, has so stressed the importance of aeronautics and meteorology that information pertaining to these subjects is among the nation's most closely guarded secrets. Aeronautics is the dominant figure in the war drama and meteorology its close collaborator.



F. W. Reichelderfer (left) presenting The Robert M. Losey Award for 1941 to Dr. Horace R. Byers.

This relation characterizes the vastly increased use of meteorology in many other war activities. We have been called upon to convert the values of the science to military purposes and the field of application for weather forecasting grows ever broader in the modern economic world.

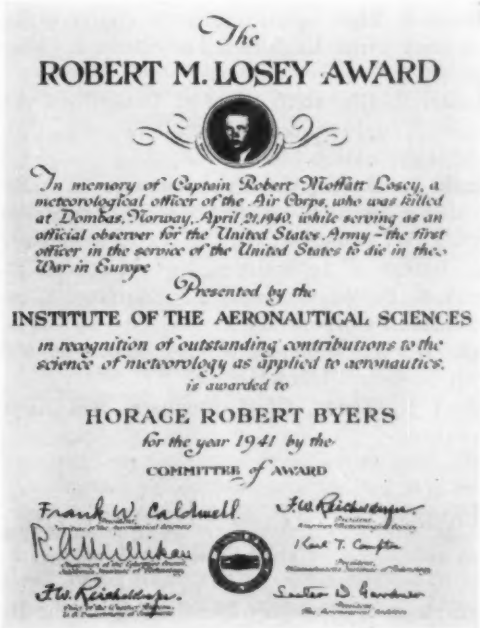
In dealing with the atmosphere, the meteorologist has to contend with one of the most complex of natural phenomena, and modern demands made upon us have called for refinements in the methods and improvements in the results. Necessity brings progress and the meteorologist today is making use of techniques of which he scarcely dreamed a few years ago. The new challenges made by the expanding needs of our military forces are bringing accelerated progress in this field and will certainly lead to many more improvements. Professional meteorologists are justly proud of what has been done in recent years. The results are due in large measure to the individual and collective leadership of a small group of young meteorologists possessed of a rare balance of scientific enthusiasm and the ability to convert their knowledge to fruitful applications.

The Losey Award for 1941 goes to one of these young men who saw the possibilities in the new techniques in meteorology and this is most appropriate from every point of view. Captain Losey, who lost his life in line of duty in Norway in 1940, was an Air Corps Officer who was pioneering in the applications of modern meteorology to military matters. The award that bears his name is intended to distinguish each year a scientist who has contributed notably to meteorology in the field of aeronautics.

The man we honor this year has earned the award, not by a single contribution, but rather by a career in the adaptation of the principles of meteorological theory and practice to the art and business of flying. His writings during the past decade cover many important studies and he has been highly successful in spreading knowledge of the modern scientific principles of meteorology.

The members composing the Committee which chose the recipient for this Award are Dr. Robert A. Millikan, Chairman of the Executive Council, California Institute of Technology, Dr. Karl T. Compton, President of the Massachusetts Institute of Technology; Frank W. Caldwell, President of the Institute of the Aeronautical Sciences; Lester Gardner, President of the Aeronautical Archives, and myself, representing the American Meteorological Society and the Weather Bureau.

Dr. Byers, for your research in air mass analysis and its applications in synoptic and aeronautical meteorology, the Institute of the Aeronautical Sciences presents you with the Robert M. Losey Award for 1941.


The
ROBERT M. LOSEY AWARD
In memory of Captain Robert Moffatt Losey, a meteorological officer of the Air Corps, who was killed at Dombas, Norway, April 21, 1940, while serving as an official observer for the United States Army - the first officer in the service of the United States to die in the War in Europe
Presented by the
INSTITUTE OF THE AERONAUTICAL SCIENCES
in recognition of outstanding contributions to the science of meteorology as applied to aeronautics,
is awarded to
HORACE ROBERT BYERS
for the year 1941 by the
COMMITTEE of AWARD
Frank W. Caldwell
Karl T. Compton
Lester D. Gardner

DR. BYERS: I am most appreciative of this Award because I enjoyed the friendship of Bob Losey. I am honored to receive it from Dr. Reichelderfer, Chief of the greatest weather bureau in the world. I also appreciate the interest that the Institute of the Aeronautical Sciences has shown in continuing to foster meteorological research as one of the important aeronautical sciences.

In the last fifteen years, with the development of aeronautics, meteorology has taken strides which it had never taken in a like period before. It is also significant that of the five institutions where meteorological research and professional training is carried on, at three of them it was started in aeronautical engineering departments. The aeronautical engineering work in many instances has gone ahead in the same manner and in collaboration with meteorological research. Meteorological literature contains such names as von Kármán, G. I. Taylor, Prandtl, and so on, which are familiar to you from the point of view of aerodynamics. Meteorology has many applications and the application to aeronautics is the most live and interesting one and the one to which I have directed most of my work.

FELLOWSHIP IN THE INSTITUTE

Certificates of Fellowship in the Institute were presented by the President to the following ten members who were elected Fellows in 1941, by the present American Fellows and Honorary Fellows, as members "who have attained a position of distinction in aeronautics and made notable and valuable contributions in one of the aeronautical sciences or aeronautical engineering"—

George W. Brady, Chief Engineer, Curtiss Propeller Division, Curtiss-Wright Corporation.

John W. Crowley, Jr., Senior Aeronautical Engineer, Langley Memorial Aeronautical Laboratory, National Advisory Committee for Aeronautics.

Ralph S. Damon, President, Republic Aviation Corporation.

William K. Ebel, Vice-President in charge of Engineering and Chief Engineer, The Glenn L. Martin Company.

Michael E. Gluhareff, Chief of Design and Aerodynamics, Vought-Sikorsky Aircraft Division, United Aircraft Corporation.

Ronald M. Hazen, Vice-President and Chief Engineer, Allison Division, General Motors Corporation.

Capt. F. W. Pennoyer, Jr., U.S.N., Engineering Division, Bureau of Aeronautics, Navy Department.

Harry A. Sutton, Aeronautical Engineer, Consolidated Aircraft Corporation.

Capt. W. W. Webster, U.S.N., Manager, Naval Aircraft Factory, Philadelphia.

Robert J. Woods, Chief Engineer, Bell Aircraft Corporation.

Honorary Membership in the Institute

Certificates of Honorary Membership in the Institute were conferred by the President on the following who were elected Honorary Members during the past year:

Hon. Robert A. Lovett, Assistant Secretary of War for Air.

Hon. Artemus L. Gates, Assistant Secretary of the Navy for Air.

Hon. Robert H. Hinckley, Assistant Secretary of Commerce for Air.

Hon. L. Welch Pogue, Chairman, Civil Aeronautics Board.

Merrill C. Meigs, Chief, Aircraft Branch, War Production Board.

President Caldwell: The Council of the Institute elects each year to Honorary Membership ten or more persons who are distinguished officials heading responsible divisions of the Government having to do with aviation. This year three of the new Honorary Members are present and two are represented by prominent Navy and Army officers.

Brig. Gen. Arnold N. Krogstad, Commander, First Air Force, Mitchel Field (on behalf of Mr. Lovett): I came here tonight to see some of my friends honored by this Institute. For some twenty-six years in the Air Corps, I have had occasion to read many of the reports and studies of the members of this Institute and have witnessed their experiments and know something about the results that they have obtained. Their efforts have made a profound influence upon the world today. It is an honor to be associated with men of such determination. In that spirit, I accept on behalf of Mr. Lovett, the Assistant Secretary of War for Air, the Honorary Membership tendered to him by the Institute of the Aeronautical Sciences.

Capt. E. M. Pace, Jr., U.S.N., Bureau of Aeronautics, Navy Department (on behalf of Mr. Gates): Mr. Gates wishes me to express his deep appreciation of the honor that is being bestowed upon him this evening and his regret at his inability to be present in person to receive it.

I would like to take this occasion to express my own appreciation and my own pleasure in being here and my fortune in Mr. Gates's unavoidable absence in being able to accept this honor that the members of the Institute of the Aeronautical Sciences are rendering to him.

Mr. Hinckley: We have been doing something about air-conditioning America. We are putting aviation in the colleges of this country. Aviation is in over 600 colleges today. More than that have participated, but our appropriations limited the number this year. We hope that in the future we shall be able to increase that number.

Of the number that have participated, 85 per cent are now giving college credits. We started with the colleges because we wanted to do everything that we could very quickly. We recognized full well that to do the kind of job that we must, we had to get these trainees, we had to get these children of ours young and tell them everything; so now we are on a program to put aviation in the high schools and the grade schools.

We must make America a nation of flyers if we expect to compete with what is going on in the world. That is important not only in the present war effort, but it will be important in the post-war effort, not only for commerce but to prevent the next war. It can be done by air-conditioning the coming generations. By air-conditioning, I mean simply making every child, male or female, as much at home in the air in this country as the South Sea Islanders are in the water.

We can do it! If we don't, we shall have no one to blame but ourselves and, in my opinion, we shall not be worthy of our heritage.

Mr. Pogue: I accept the Honorary Membership in the Institute of the Aeronautical Sciences as being related to my responsibilities as a public servant. I know full well that it behooves me to discharge to the very best of my ability the responsibilities that have been placed in my hands, because it is in that way that I shall aspire to merit the honor you do me tonight.

The Institute is, as I understand it, organized for the purpose of promoting the application of science in the development of aircraft. Scientific attitude and approach are the necessary background for membership. I adopt and profess the scientific technique in the development of governmental regulation of aircraft. The finest theory or law is impotent if it does not meet successfully the test of that practical question of scientists: Does it work?

When the dry and solid wood constituting the experience of the daily task is lighted with the fire of imagination, it releases creative power. To the scientist, the daily experience of work is the textbook, the test tube, and the laboratory. To the public servant, it is the history of past problems, the current arguments and contentions, and the needs of the nation. In each case the scientific method of careful experimentation, intelligent selection and daring imagination is our own real hope of progress.

Devotion and courage are essential for the proper discharge of a trusteeship of any substantial part of the field of aviation, whether it be engineering, production, operation or regulation. Aviation is a young industry, exhausting the imagination in its potentialities. It has already become an indispensable arm of our life, both in war and in peace, at home and abroad. It will continue to readjust many of our relationships and ways of life. It is indeed a precocious child of our civilization.

In closing, I would like to add my small word about civilization. One hears it suggested that civil aviation may be arrested, now that we are at war; but no matter what the outcome of this conflict, the future of civil aviation is bound to be bright. The

mind of man has thrilled to it, and it will never let it go. In the meantime, I, for one, feel the conviction that there is no substitute for the speed of civil aircraft at a time when speed on every front is the minimum price that must be paid if we are to win. Better designs, higher speed, and wider use of civil aircraft will be tremendously effective in this war effort and those facts are even now self-evident. Again I would like to thank you for the Honorary Membership in so distinguished an association of scientists and leaders.

MR. MEIGS: I accept this great honor on behalf of the Aircraft Branch of OPM that was, and WPB that is. When I went on this job in Washington, I knew very little about aviation. I knew something about people. I asked the air services to give us a plan that they wanted us to work on which could be put on one sheet of paper. Then I asked them to pick the men they wanted to work for them, and with them. They did that and very wisely, of course, they picked for my Chief Assistant and the man that really runs the place, an ex-president of this Institute.

Ted Wright, having been chosen by you as President of your organization, we knew to be capable and we knew that with him we would succeed. It is because of Ted and the men which he and the air services picked to work for and with them and with the manufacturers that I stand here tonight to accept this great honor which you are conferring upon them through me.

As a reporter, watching carefully throughout the year, as history is being written, I would like to say that, despite our columnists, our committees, and what not, the record of production in aircraft for 1941 will be a record that has never been even approached in performance in the history of the human race.

On behalf of our Aircraft Branch, I want to thank you one and all, the air services, the manufacturers, the engineers, for bearing with us, for allowing us to work with you. It has been a great experience. We hope to be permitted to work with you throughout the duration. We will do our best for you.

ANNOUNCEMENTS OF GIFTS TO THE INSTITUTE

Lester D. Gardner, President of the Aeronautical Archives and Executive Vice-President of the Institute, gave a brief résumé of the benefactions that had been made to the Institute.

MR. GARDNER: It is customary for the Institute to ac knowledge generous gifts publicly at its meetings and to remember those whose confidence and foresight have placed it on such a firm foundation, financially.

We remember two friends, who have passed on, who made contributions which, in those early days, gave evidence of confidence in the future of the Institute. Dr. S. A. Reed and Mr. Edmund C. Lynch established funds of $10,000 each, one for an award and the other to endow the Wright Brothers Lecture. The Sperry family gave us $10,000 for the Lawrence Sperry Award. But gifts of money represent only a part of the ever growing assets of the Institute.

Our Libraries have been given several valuable collections, notably those of Colonel Aldrin, Mr. Hanscom, and, this year, Mr. E. P. Warner. These accessions have not only enabled the Institute to render a greater service by an enlarged library, but also to acquire many technical books which are rare and out of print.

Last year we paid our compliments to a lady who had presented to the Institute her great collection of aeronautical prints, music, trade cards, book plates, posters and rare books. This gift has placed the Archives of the Institute in a notable position as a repository for all forms of aeronautica. Mrs. Landauer is continually adding to the collections and this year has given us many original aeronautical paintings which are an adornment to the walls of the Institute offices.

As you may remember, Mr. Paul Kollsman and the Square D Company gave the Institute $50,000 last year to be used at the rate of $10,000 a year for loaning books by mail, without charge, to anyone in the United States. This service has had such a remarkable success that Mr. Kollsman wished to endow it permanently. He therefore has assured us of $25,000 more so that the fund may remain at $65,000 and the interest be used for the upkeep.

There is no one who has shown a greater interest in the progress of the Institute than Sherman Fairchild. He persuaded Mr. Lynch to give us $10,000 and now he has given a fund of $25,000 to issue technical reports and translations which will, we are sure, render a great service to aeronautical engineers.

And lastly is a splendid gift from the Pacific Coast. An old friend and one of the founders of the Institute, R. H. Fleet, sent a check for $10,000, the use of which has not as yet been decided.

I have given you a summary of ten years of financial contributions to the Institute. You all know of the fine support we receive from members and the aircraft industry.

You may be interested to know that the funds of the Institute to be used for the benefit of the aeronautical profession now stand at over $170,000. And you younger men are destined to see the Institute become one of the most liberally endowed scientific societies in the world. I know of over $600,000 of bequests in wills to the Institute from men who are in this room now. We believe there are many others.

The Institute can look forward to the next ten years, and other decades to follow, with confidence that the interest of members and the generosity of donors will make possible the rendering of an ever increasing service to the aeronautical profession and that it will continue to be worthy of the inspiring message we have received from the President of the United States.

INDUCTION OF PRESIDENT OF THE INSTITUTE FOR 1942

Hall L. Hibbard, Vice-President and Chief Engineer of Lockheed Aircraft Corporation, was inducted into office as President of the Institute for 1942 by the retiring President.

PRESIDENT CALDWELL: My term as President of the Institute of the Aeronautical Sciences has now come to an end. It has been an honor to serve the Institute. I appreciate the cooperation which I have received from the officers and the Council and thank them for their support. The efficiency of the staff has been so outstanding that it has been a great pleasure to work with them.

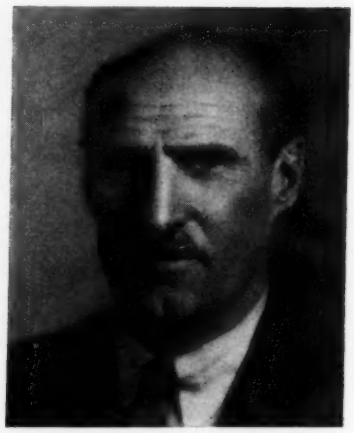
I am particularly happy at this time to turn over the Presidency to a representative of the great aeronautical industry of the Pacific Coast. I could embarrass Hall Hibbard by saying a great many things about him. I don't need to. Fleets of Lockheed airplanes are telling his story. In civil air transport we have learned to appreciate their excellence. In the military field they are the terror of our enemies.

I now turn over the Presidency of the Institute of the Aeronautical Sciences to you, Mr. Hibbard.

PRESIDENT HIBBARD: I deeply appreciate the honor of being asked to serve as President of the Institute of the Aeronautical Sciences for the year 1942. I fully recognize the responsibility connected with this honor. In normal times it is great enough, but in this time of war the responsibility is indeed greater. The year 1942 will be the most important year in the history of American aviation. During these next twelve months the Institute will have heavy obligations and, as its President, I shall carry out my duties to the best of my ability.

Grover Loening
Vice-President

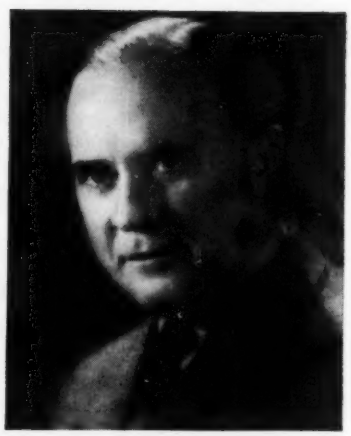
Hall L. Hibbard
President



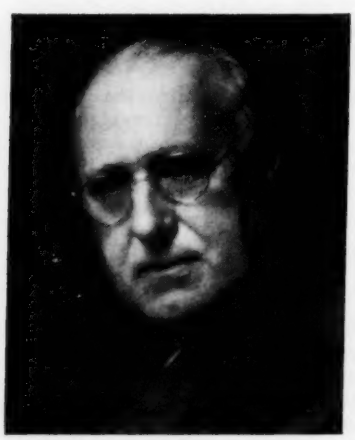
C. S. Jones
Vice-President

J. G. Vincent
Vice-President

Officers of the Institute for 1942



Thomas A. Morgan
Vice-President



Lester D Gardner
Executive Vice-President

Earl D. Osborn
Treasurer

C. E. Sinclair
Secretary

Institute of the Aeronautical Sciences Tenth Annual Meeting

THE Tenth Annual Meeting of Members of the Institute of the Aeronautical Sciences Inc., was held in New York on the last Wednesday of January, as required by the Constitution and By-Laws, in the Pupin Physics Laboratories Building, Columbia University, at 5:00 p.m. on January 28, 1942. Frank W. Caldwell, President of the Institute, presided. C. E. Sinclair, Secretary, acted as secretary of the meeting.

Clark B. Millikan, appointed by the President as Teller of proxies, reported that he had received and counted 375 valid proxies for voting at the Annual Meeting—a quorum of the voting members.

Dr. J. C. Hunsaker, on behalf of the Nominating Committee, placed in nomination the following members for election to vacancies on the Council: Charles Froesch, for a term of one year; J. Carlton Ward, Jr., for a term of one year; L. S. Hobbs, for a term of two years; W. A. M. Burden, Charles H. Colvin, R. T. Goodwin and Roger Wolfe Kahn, for terms of three years. On motion duly made, seconded and carried, they were unanimously elected. The following were nominated and elected in like manner to serve on the Advisory Board for a term of one year: John D. Akerman, Lawrence D. Bell, Vincent Bendix, Lyman J. Briggs, Jack Frye, P. G. Johnson, J. H. Kindelberger, F. K. Kirsten, A. L. Klein, Paul Kollsman, I. Machlin Laddon, Bruce G. Leighton, A. I. Lodwick, A. E. Raymond, F. W. Reichelderfer, J. T. Trippe, E. P. Warner, E. Burke Wilford, John E. Younger, A. D. Tuttle.

J. H. Kimball placed in nomination the following Past Presidents of the Institute to serve as the Nominating Committee for 1942: Frank W. Caldwell, G. W. Lewis, Glenn L. Martin, Clark B. Millikan and T. P. Wright. On motion duly made, seconded and carried, they were elected.

The Annual Reports of the President, the Treasurer and the Secretary were read and approved as follows:

THE PRESIDENT'S ANNUAL REPORT

At the last Annual Meeting a prudent policy of restricting the expansion of Institute activities was adopted. This policy has been carried out and expansion has been primarily limited to the services rendered by the Aeronautical Archives which are endowed by special funds contributed by generous donors, notably by Paul Kollsman.

The increase in membership has been satisfactory and normal, as will be seen from the Secretary's report.

The report of the Treasurer will show that the Council and Officers have operated the Institute within its income. There has been a substantial increase of restricted assets of the Institute resulting from additional gifts. In a recent report, the funds of the Institute were set at $164,000. By the careful administration of funds entrusted to its care, the Institute has attracted further contributions. It is a great satisfaction to report that every fund entrusted to the Institute is now at a higher valuation than when it was received. The policy of the Council is to conserve funds rather than to seek high income.

With the cooperation of the aircraft manufacturers in the Los Angeles area, the Institute established the Pacific Aeronautical Library. It is now rendering a service which will be amplified by gifts and purchases of books and magazines. Major Gardner, in his report at the Annual Honors Night Dinner, has recorded the recent gifts to the Institute. Speaking for the Officers and the Council, I express their appreciation for such a remarkable evidence of confidence in the Institute.

The Libraries of the Institute have grown so that they may be ranked as second, only, to the Library of Congress in scope and numbers of aeronautical books. W. A. M. Burden has made generous transfers of books, reports and files of clippings. The outstanding accession was the gift by E. P. Warner of five hundred books from his library. As many of these were collected years ago and are out of print, they have added greatly to the service the Institute may render.

I wish to express the appreciation of the Institute to others, too many to mention in this report, for gifts of books, models, prints, clippings and other material which is making the Aeronautical Archives such an incomparable reference source for aeronautical information.

The Journal of the Aeronautical Sciences continues to maintain its standard of technical excellence although, under existing conditions, the publication of much important material is restricted. The appreciation of the Institute is due to the Editors and Editorial Board who have given such helpful service in the evaluation of papers.

The Aeronautical Review has filled a definite need and is providing a valuable service by keeping aeronautical engineers informed about the progress of aeronautical development as reflected in current magazines and new books.

The Institute now has forty-one Student Branches and eight Sections, and all have held numerous meetings. To the officers of these Branches and Sections the Institute expresses its appreciation of the excellent programs they have been able to provide for members.

To the other Officers, the Council and the staff of the Institute, I wish to express my appreciation for their cooperation and assistance in making the past year a memorable one in our history.

As the Institute enters its second decade of service to the Aeronautical profession, its future is assured by the loyal support of a carefully selected membership and able leaders who are willing to give of their time and ability for its direction.

FRANK W. CALDWELL

THE TREASURER'S ANNUAL REPORT

The report of the Treasurer of the Institute for our fiscal year which ended September 30, 1941, reflects the generous contributions made in 1940 to the Institute but does not include the more recent gifts.

Members will be glad to know that the Institute was operated last year within its income. It is not the policy of your Officers and your Council to expand the activities of the Institute to any great extent in these uncertain times. They look forward to a period when support may not be as general as it is now.

INSTITUTE OF THE AERONAUTICAL SCIENCES, INC.

For the Fiscal Year October 1, 1940, to September 30, 1941

Consolidated Balance Sheet

ASSETS

General Assets		
Cash on Hand and in Bank		$ 10,072.01
Deposits and Advances		875.00
Accounts Receivable		2,712.92
The Benefactor Membership Fund:		
U.S. Treasury Bonds at Par Value (Market Value $13,344.00)		12,000.00
Office Furniture & Equipment	$12,870.41	
Less: Reserve for Depreciation	8,062.55	4,807.86
Prepaid Expenses		566.40
Pacific Aeronautical Library Advance		1,063.05
Library—Books, Prints, Models, Pictures, etc.		1.00
Aeronautical Index		1.00
Total General Assets		$ 32,099.24
Investment of Restricted Funds		
The S. A. Reed Fund:		
U.S. Treasury Bond at Par Value (Market Value $11,120.00)	$10,000.00	
Reserve—Cash on Deposit	622.11	10,622.11
The Lawrence Sperry Fund:		
U.S. Treasury Bonds at Par Value (Market Value $6,672.00)	$ 6,000.00	
Reserve—Cash on Deposit	549.94	6,549.94
The Vernon Lynch Fund:		
Melville Shoe Corporation Stock (Market Value $9,646.75)	5,004.00	
Peoples Drug Stores, Inc., Stock (Market Value $8,880.00)	5,272.50	
Uninvested Principal	58.50	
Reserve—Cash on Deposit	1,913.06	12,248.06
The Paul Kollsman Library Fund:		
Cash on Hand and Receivable		40,064.05
Total Investment Assets		69,484.16
Total Assets*		$101,583.40
* Pledges for future gifts have been made by donors of:		
The Lawrence Sperry Fund		$ 4,000.00
Unrealized appreciation on investments		11,327.75
		$ 15,327.75
Assets as above listed		101,583.40
		$116,911.15

LIABILITIES, FUNDS AND UNEXPENDED INCOME

General Liabilities		
Accounts Payable		$ 7,962.12
Deferred Income:		
Unearned Corporate Member Dues	$9,690.00	
Unearned Subscriptions	2,460.58	
Corporate Member Dues Paid in Advance	250.00	
Member Dues Paid in Advance	909.25	13,309.83
Unexpended Income:		
Balance October 1, 1940	8,331.65	
Unexpended Income—September 30, 1941	2,495.64	10,827.29
Total General Liabilities		$ 32,099.24
Restricted Funds		
The S. A. Reed Fund:		
Principal	$10,000.00	
Unexpended Income—Reserve	622.11	10,622.11
The Lawrence Sperry Fund:		
Principal	6,000.00	
Unexpended Income—Reserve	549.94	6,549.94
The Vernon Lynch Fund:		
Principal	10,335.00	
Unexpended Income—Reserve	1,913.06	12,248.06
The Paul Kollsman Library Fund:		
Principal		40,064.05
Total Restricted Funds		69,484.16
Total Liabilities, Funds and Unexpended Income		$101,583.40

Statement of Income and Expenses

INCOME

Dues		$ 38,187.14
Entrance Fees		1,340.00
Benefactor and Donor		950.00
Emblems—Net		641.21
Miscellaneous		490.25
		$ 41,608.60
Excess of Expenses on Publications (see detail)		3,377.00
Total Income		$ 38,231.60

EXPENSES

Administration, Clerical and Accounting		$ 13,548.61
Award Expenses and Certificates of Membership		1,228.45
Electricity, Telephone and Telegraph		603.39
Guest Reception and Travel		1,140.64
Office Expense, Supplies and Printing		1,244.06
Postage		1,496.59
Rent		2,055.12
Miscellaneous		813.45
Depreciation		546.61
Uncollectable Accounts		131.00
		$ 22,807.92
Aeronautical Archives Maintenance		12,928.04
Total Expense		35,735.96
Net Unexpended Income for the Year Ended September 30, 1941		$ 2,495.64

Naturally the demands on the Institute for service have increased greatly, but fortunately the Institute has been able to meet these requirements by the use of special funds provided by donors.

The total assets and unexpended income of the Institute have increased as follows:

	Total Assets	Unexpended Income by Year	Total Unexpended Income
1933	$ 1,176.92	$ 705.01	$ 705.01
1934	7,717.18	3,465.63	4,170.64
1935	6,338.22	462.48	4,633.12
1936	20,906.90	261.43	4,894.55
1937	23,497.66	408.14	5,302.69
1938	35,776.91	281.93	5,584.62
1939	46,149.64	918.37	6,502.99
1940	67,995.56	1,828.56	8,331.65
1941	101,583.40	2,495.64	10,827.29

The foregoing assets are at book values. At the market value the assets on September 30 were $112,911.15. A statement as of January 28 would show over $170,000 if commitments from donors were included.

These figures do not include many of the tangible assets which are carried on the books at $1. The indexes of the Institute were assembled by the Work Projects Administration at an expense of over $300,000. The Paul Kollsman and Pacific Coast Libraries, which have over 6,000 books at present, represent a replaceable value of $15,000 to $25,000. Our furniture and fixtures cost $12,870.41 and have been depreciated to $4,807.86.

Detail of Journal and Review Income and Expense

INCOME

Subscriptions		$ 32,878.03
Advertising Receipts		20,741.74
Reprints		79.64
Income		$ 53,699.41

EXPENSES

Administration, Editorial, Clerical & Accounting		$ 20,074.06
Engraving, Postage and Printing		26,830.31
Office Expense, Supplies, Printing		1,561.70
Rent		2,055.12
Agent's Commissions & Discounts		3,180.08
Promotion, Travel and Miscellaneous		2,225.14
Electricity, Telephone & Telegraph		603.39
Depreciation		546.61
Expenses		57,076.41
Excess of Expenses—Chargeable to Institute Income		$ 3,377.00

The biographical and subject files, the great collection of aeronautical prints, original paintings, music, trade cards, book plates and posters presented by Mrs. Landauer, and over one hundred models, many framed photographs and prints acquired by the Institute through gifts should all be included in our assets but cannot be appraised for audit.

Our liabilities to others are current, as it has been the policy of the Council to authorize no expenditures beyond the Institute's income. While the surplus or unexpended income is over $10,000, this apparent gain is represented by many intangibles rather than by cash.

The books have been audited by a firm of public accountants and they have reported that our books are kept in accordance with good accounting practice and that the financial statement submitted herewith reflected the state of the Institute's operations as of September 30, 1941.

GROVER LOENING

THE SECRETARY'S ANNUAL REPORT

The increase in the Institute's membership over the past year has included many aeronautical engineers from the greatly expanded aviation companies and graduates from aeronautical schools. It has also included representation from new companies and those recently undertaking aeronautical production as well as a considerable body of engineers experienced in other fields who have lately turned to aeronautical work.

Following is the membership by grades as of January 1, 1942:

Honorary Members	17
Honorary Fellows	18
Fellows	185
Associate Fellows	499
MEMBERS	633
Industrial Members	172
Technical Members	1,690
Total graded members	3,214
Student Members	944
Total Membership	4,158

The net increase in the number of graded members (above Student Member grade) was 426 during the past twelve months. Enrollment of Student Members was 314 more than that of the preceding year, making a total net increase of 740 members.

The Founders' Meeting or First Annual Meeting held in this room on January 26, 1933, began the activities of the Institute with a membership of 400. At today's meeting, beginning our tenth year, that original membership figure has been increased tenfold. The present total of over 4,000 represents, we believe, a membership actively interested in the work of the Institute, since applications are given only to persons who have requested them, who have attended our meetings or have been proposed by members. This year we again urge our members to propose any of their colleagues who would be interested in membership in the Institute.

At the beginning of this year seventy-three companies were affiliated with the Institute as Corporate Members. Of these, twenty-three were added during 1941. The support of our work by Corporate Members has been most gratifying and is appreciated by the membership.

Local Sections of the Institute are now organized in eight aviation centers throughout the country, serving about 700 Institute members in addition to their local affiliate members. New Sections in San Diego and Detroit were organized during the past year. Under present conditions, it has been found best to carry on our meeting activities, other than the Annual Meeting, in the form of single sessions at evening meetings of the various Sections to conform with special requirements and conditions in their localities.

Our 944 Student Members are organized in Branches in forty-one schools and colleges, seven of them having been organized in 1941. Mimeographed lectures, illustrated with projection slides, were sent to Student Branches for their use at meetings and assistance was given in providing motion pictures and special lecturers. Meetings of Student Branches last year had a total attendance of approximately 5,000 persons.

A new Certificate of Membership of larger size and more appropriate text and design was approved by the Council and made available to members last Fall. Recently, Membership Cards were sent to all members to be used as identification and for admission to meetings. The insignia and credentials of membership in the Institute have come to indicate a degree of prestige in the aeronautical profession which reflects the high standing that the Institute has attained through the support and achievements of its members over the past decade.

C. E. SINCLAIR

REPORT OF THE PRESIDENT OF THE AERONAUTICAL ARCHIVES

Lester D. Gardner, Executive Vice-President of the Institute and President of the Institute's Aeronautical Archives, presented the following report on the activities of the Archives:

The Aeronautical Archives were opened April, 1940. There are four divisions. The Burden Library, with 12,000 aeronautical books and pamphlets, is one of the most comprehensive reference libraries in the world. The Paul Kollsman Library has been greatly enlarged through gifts and purchases and is rendering a valued service by lending books. The Aeronautical Index and Subject Files are in constant use as a guide and source of reference for readers. The fourth division is the collection of aeronautical prints, posters, trade cards, music, book plates, Christmas cards and calendars.

The usefulness of the Archives is indicated by the following report:

RECORD OF USERS AND VISITORS

Period	Days Open	Readers	Telephone Calls	Total Users	Visitors
April–Dec. 31, 1940	195	480	130	610	218
Jan.–Dec. 31, 1941	271	1,030	354	1,384	201
Totals	466	1,510	484	1,994	419

Approximately 868 separate individuals and organizations made 2,054 personal and telephone calls for information during the 482 days that the Aeronautical Archives has been open from April 8, 1940, through January 21, 1942.

The growth of The Paul Kollsman Library in its first year of service is shown by the following:

Total Library Membership	1,629	Total Number of Books Loaned	1,993

BOOKS IN LIBRARY

Accessions	4,820
Duplicates	537
Total	5,357
Pacific Aeronautical Library	947
Total	6,304

Of the above 6,304 books in both libraries, 429 have been purchased from the Kollsman Fund, the others having been received as gifts and for review.

The list of organizations using the Archives is impressive. Fifty-two of the leading magazines, newspapers, and publishers used the libraries for reference information, some many times. Eighteen schools and universities sent their students to refer to books in the libraries. There were 132 companies which were served by giving their representatives information and permitting them to refer to magazines and books.

The Pacific Aeronautical Library was opened in Hollywood in October, 1941, and is providing the aeronautical companies in the Los Angeles area with a service which supplements the mail service of the Aeronautical Archives.

Not the least important of the activities of the Archives has been the collecting of copies of books, pamphlets, patents, magazines, and newspaper clippings published in the United States before 1900. Other countries have taken pride in the work of pioneers in their aeronautical history. The work of American pioneers has never been adequately presented. This important field is now being studied and it is hoped that a book will be published in 1942 which will show that the United States has a background of aeronautical experimentation, before the success of the Wright Brothers' work, which should be known and regarded with pride by Americans.

To all who have presented gifts to the Aeronautical Archives, the appreciation of the Institute is again expressed.

LESTER D. GARDNER

The Secretary presented the list of honors conferred by the Institute in 1941:

The Sylvanus Albert Reed Award to Dr. Theodore von Kármán.

The Octave Chanute Award to Melvin N. Gough.

The Lawrence Sperry Award to Ernest G. Stout.

The John Jeffries Award to Harry G. Armstrong.

The Robert M. Losey Award to Horace R. Byers.

(Citations for the above awards are published in the account of the Honors Night and Tenth Anniversary Dinner in this issue of the Journal.)

The Wright Brothers Lectureship to R. V. Southwell, who presented the Lecture on December 17, 1941, on the subject "New Pathways in Aeronautical Theory."

Fellowship in the Institute to George W. Brady, John W. Crowley, Jr., Ralph S. Damon, William K. Ebel, Michael E. Gluhareff, Ronald M. Hazen, F. W. Pennoyer, Jr., Harry A. Sutton, W. W. Webster and Robert J. Woods.

Honorary Membership in the Institute for the year 1942 conferred by the Council upon Lt. Gen. H. H. Arnold, Griffith Brewer, Dr. Lyman J. Briggs, Hon. Artemus L. Gates, Hon. Harry F. Guggenheim, Hon. Robert H. Hinckley, Dr. J. C. Hunsaker, Dr. G. W. Lewis, Hon. Robert A. Lovett, Merrill C. Meigs, Prof. George B. Pegram, Hon. L. Welch Pogue, F. W. Reichelderfer and Rear Admiral J. H. Towers.

On motion duly made, seconded and carried a resolution was passed expressing to President Nicholas Murray Butler and Dean George B. Pegram of Columbia University the appreciation of the membership of the Institute for the cooperation and gracious hospitality that had been extended to the Institute for the holding of its meetings throughout the ten years since the Founders' Meeting.

The Secretary announced the Officers of the Institute for 1942 elected by the Council at its meeting on January 7, 1942:

President—Hall L. Hibbard
Vice-Presidents—C. S. Jones
Grover Loening
J. G. Vincent
Thomas A. Morgan
Executive Vice-President—Lester D. Gardner
Treasurer—Earl D. Osborn
Secretary—C. E. Sinclair
Assistant Treasurer—George R. Forman
Controller—Joseph J. Maitan

There being no further business, the meeting then adjourned.

C. E. SINCLAIR, *Secretary*

Tenth Annual Meeting Technical Sessions

The Technical Sessions of the Tenth Annual Meeting were held in the Pupin Physics Laboratories Building, Columbia University, New York, January 28–30, 1942. Over 800 persons registered to attend the sessions, which were open only to members or persons recommended by members of the Institute. The 67 papers presented at the various sessions are listed below.

Preprints are now available only for those papers that are marked with an asterisk (*). For those not so marked, preprints were either not issued or the original supply was completely distributed at the meetings. Members wishing copies of the remaining preprints should write to the Institute immediately, as requests will be filled in order of receipt. Those papers which are released for publication and are approved by the Editorial Board will be published in forthcoming issues of the Journal.

WEDNESDAY, JANUARY 28

9:15 a.m. **STRUCTURES, Part 1**

Chairman:
EUGENE E. LUNDQUIST, National Advisory Committee for Aeronautics

***The Lateral Instability of Unsymmetrical I-Beams**—H. N. Hill, Aluminum Company of America

A Theory for the Buckling of Curved Shells—Hsue-shen Tsien, California Institute of Technology

***Elastic Theory as a Tool in Sheet Metal Forming Problems**—F. R. Shanley, Lockheed Aircraft Corporation

Load Factors Obtained on Civil Airplanes in Acrobatic Maneuvers—Edward I. Ryder, Civil Aeronautics Administration

***Stress Analysis of Rings for Monocoque Fuselages**—N. J. Hoff, Polytechnic Institute of Brooklyn

9:15 a.m. **POWER PLANTS**

Chairman:
R. N. DUBOIS, Packard Motor Car Company

Notes on a Propeller Hub Development—C. S. MacNeil, Aeroproducts Division, General Motors Corporation

Aircraft Engine Installation and Its Effects on Engine Design—E. C. Sulzman, Wright Aeronautical Corporation

***The Correction of Engine Output to Standard Conditions**—Donald S. Hersey, Pratt & Whitney Aircraft Division, United Aircraft Corporation

2:00 p.m. **STRUCTURES, Part 2**

Chairman:
JOHN E. YOUNGER, University of Maryland

***Bending and Torsional Design Charts for Round Chrome-Molybdenum Tubing**—Vincent C. Trimarchi, Rensselaer Polytechnic Institute

Review of Present Day Welding of Aircraft Steels—A. J. Williamson and J. P. Dods, Summerill Tubing Company

***Design and Static Tests of a Magnesium Alloy Wing**—Emerson W. Conlon, University of Michigan and John C. Mathes, Dow Chemical Company

Resin-bonded Wood Laminates for Shell Type Aircraft Structures—Alfred A. Gassner, Duramold Aircraft Corporation

***Ground Vibration Tests**—D. Pengelley, Airplane Division, St. Louis Plant, Curtiss-Wright Corporation

2:00 p.m. **RADIO AND INSTRUMENTS**

Chairman:
W. A. REICHEL, Pioneer Instrument Division, Bendix Aviation Corporation

***A Simple Method of Applying the Compressibility Correction Factor in the Determination of True Airspeed**—W. C. Schoolfield, Vought-Sikorsky Aircraft Division, United Aircraft Corporation

***The Automatic Radio Compass**—Wilbur L. Webb and Gerald O. Essex, Bendix Radio Corporation Division, Bendix Aviation Corporation

***The Space Time Recorder**—F. N. M. Brown, University of Notre Dame

8:00 p.m. **DESIGN**

Chairman:
FRED E. WEICK, Engineering and Research Corporation

Tricycle Landing Gear Design—E. S. Jenkins and A. F. Donovan, Airplane Division, Buffalo Plant, Curtiss-Wright Corporation

Fatigue Failures Affecting Air Transport Aircraft—Harold E. Hoben, American Airlines

New Developments in Simplified Control—Ralph H. Upson, Stout Skycraft Corporation

***Dynamic Balancing as Applied to Aircraft Propellers**—R. D. Speas and J. C. Luttrell, American Airlines

Beryllium in Aircraft Design—E. Burke Wilford, Pennsylvania Aircraft Syndicate

THURSDAY, JANUARY 29

9:15 a.m. **MATERIALS, Part 1**

Chairman:
C. F. NAGEL, Aluminum Company of America

***Use of Plastics and Allied Materials in Aircraft Construction**—George W. DeBell, The Glenn L. Martin Company

A New Type of Preformed Structural Plastic—A. A. Bates, Westinghouse Electric Research Laboratories

***Advances in Production and Assembly of Plywood in Aircraft Production**—Hugh G. Bersie and Edwin R. Clarke, Haskelite Manufacturing Company

A Few Engineering Aspects of Elastic Behavior of Anisotropic Materials—Michael Watter, Edward G. Budd Manufacturing Company

***Economic Advantages of Certain Aluminum Alloys for Aircraft Construction**—Kirby F. Thornton, Aluminum Company of America

***Aluminum Alloys for Aircraft**—T. L. Fritzlen, Reynolds Metals Company

9:15 a.m. **ROTATING WING AIRCRAFT**

Chairman:
RALPH H. MCCLARREN, The Franklin Institute

Rotor Bending Moments in Plane of Flapping—Alexander Klemin, New York University, assisted by Wayne Wiesner, Kellett Autogiro Corporation, and W. C. Walling, New York University

Recent Developments and Flights of the VS-300 Helicopter—Igor I. Sikorsky, Vought-Sikorsky Aircraft Division, United Aircraft Corporation

***Rotor Blade Design**—Richard H. Prewitt, Kellett Autogiro Corporation

***General Flight Analysis of the Helicopter**—Montgomery Knight, Georgia Institute of Technology

2:00 p.m. **MATERIALS, Part 2**

Chairman:
A. V. DE FOREST, Massachusetts Institute of Technology

***Flash Butt Welding of Chrome Moly Steel**—W. Stuart Evans, Airplane Division, St. Louis Plant, Curtiss-Wright Corporation and V. V. Netchvoldoff, Hill Equipment Engineering Company

***Control Procedure of Torch Welding in Aircraft**—Eric Dudley, Airplane Division, Buffalo Plant, Curtiss-Wright Corporation

***X-Ray of Aircraft Castings—Its Control and Value**—B. C. Boulton, Lockheed Aircraft Corporation

***Effect of Magneto Field Distribution in Magnetic Inspection**—F. L. Fuller, Ranger Aircraft Engines Division, Fairchild Engine & Airplane Corporation

Tension and Compression Stress-Strain Characteristics of Cold-Rolled Austenitic Chromium-Nickel and Chromium-Manganese-Nickel Stainless Steels—Russell Franks and W. O. Binder, Union Carbide and Carbon Research Laboratories

2:00 p.m. PHYSIOLOGIC PROBLEMS, Part 1

Chairman:
ARNOLD D. TUTTLE, United Air Lines Transport Corporation

Physiological and Psychomotor Tests in the Selection of Pilots—Ross A. McFarland, Harvard University

Gas Exchange in the Lungs at High Altitudes—David B. Dill and F. G. Hall, U.S. Army Aero Medical Research Laboratory

Auditory Sensitivity Under Conditions of Anoxia—Clifford P. Seitz and G. M. Smith, College of the City of N. Y.

The Problems Inherent in the Protection of Flying Personnel Against the Temperature Extremes Encountered in Flight—Otis O. Benson, Jr. and Ernest A. Pinson, U.S. Army Aero Medical Research Laboratory

The Physiologic Aspects of a Free-Fall Parachute Jump—Andrew C. Ivy, Northwestern University, and Arthur H. Starnes

8:00 p.m. PHYSIOLOGIC PROBLEMS, Part 2

Chairman:
JOHN G. JENKINS, University of Maryland

General Review of the C.A.A.-N.R.C. Research Program—J. G. Jenkins, University of Maryland

Test and Non-Test Predictors of Pilot Competency—J. W. Dunlap, University of Rochester

Analysis of Pilot Performance During Standard Flights—Morris S. Viteles, University of Pennsylvania

Analysis of Instruction by Recording Instructor-Student Conversations During Flight—E. Lowell Kelly, Purdue University

Instruments for Recording Tension During Flight—A. C. Williams, Jr., Bureau of Aeronautics, Navy Department

Research and the C.A.A. Pilot Training Program—Dean R. Brimhall, Civil Aeronautics Administration

FRIDAY, JANUARY 30

9:15 a.m. METEOROLOGY, Part 1

Session Prepared in Cooperation with the American Meteorological Society

Chairman:
C. F. BROOKS, Blue Hill Observatory, Harvard University

Convection Currents in the Low Atmosphere—K. O. Lange, Blue Hill Observatory, Harvard University

Further Contributions on the Structure of the Weather on Mt. Washington—Victor Conrad, Harvard University

Certain Applications to North America of P. Queney's Theory on the Influence of Relief upon the Dynamics of the Air—Walter M. Elsasser, Blue Hill Observatory, Harvard University

A Note on Determining the Universal Turbulance Constant in the Atmosphere—Benjamin G. Holzman, U.S. Weather Bureau

***Guide Vanes for the Cup Anemometer**—Alexander Klemin and W. C. Walling, New York University

9:15 a.m. AERODYNAMICS, Part 1

Chairman:
A. M. KUETHE, University of Michigan

A New Two-Parameter Model Suspension System for the GALCIT 10-Ft. Wind Tunnel—Arthur L. Klein, Peter V. H. Serrell and Clark B. Millikan, California Institute of Technology

Wall Interference Effects on Stalling and Drag in an Elliptical Wind Tunnel—Joseph G. Gavin, Jr., and Rudolph W. Hensel, Massachusetts Institute of Technology

***A Kinetic Energy Correction to Predicted Rate of Climb**—Frederick C. Phillips, The Glenn L. Martin Company

2:00 p.m. METEOROLOGY, Part 2

Chairman:
F. W. REICHELDERFER, U.S. Weather Bureau

The Ten Thousand Foot Constant Level Chart and Its Use in Weather Forecasting—E. J. Minser, Transcontinental & Western Air

Recent Investigations Concerning the Nature of Thunderstorms and Their Electrical Manifestations—L. P. Harrison, U.S. Weather Bureau

Lightning and Aircraft—Otto E. Kirchner and W. A. Petrasek, American Airlines

Open Discussion of Airways Weather Service and Related Problems

2:00 p.m. AERODYNAMICS, Part 2

Chairman:
WILLIAM BOLLAY, Bureau of Aeronautics, Navy Department

Propeller Forces due to Yaw and their Effect upon Airplane Stability—L. B. Rumph, R. J. White and H. R. Grumman, Airplane Division, St. Louis Plant, Curtiss-Wright Corporation

***Vector Solution of the Three Degree Case of Wing Bending, Wing Torsion, Aileron Flutter**—Lee Arnold, Republic Aircraft Corporation

***Further Developments of the Theory of Propeller Tip Interference**—Albert Gail, University of Minnesota

8:00 p.m. AIR TRANSPORT

Chairman:
CHARLES FROESCH, Eastern Air Lines

Air Express and Freight, the Past, Present and Future—C. G. Peterson, Railway Express Agency

***Operating Requirements for Cargo Transportation**—Charles P. Graddick, United Air Lines Transport Corporation

Development and Application of the Curtiss-Wright Combustion Heater—Joseph J. Jerger, Curtiss-Wright Corporation

Flight Test Organization, Procedures, and Crew Training—Albert C. Reed and William F. Milliken, Jr., Boeing Aircraft Company

***Economic Effects of Airport Size and Airway Deficiencies on Air Transportation**—A. E. Blomquist, Eastern Air Lines

Institute Notes

New Corporate Member

Allison Division, General Motors Corporation, Indianapolis, Indiana, has recently become affiliated with the Institute as a Corporate Member. The Allison company, which began as an experimental laboratory in 1916, now has in production the V-1710 series of 12 cylinder, vee-type, liquid cooled aircraft engines which are used in several types of pursuit and interceptor airplanes of the Air Forces of the United States and its allies.

Gifts to the Archives

The Aeronautical Archives of the Institute have recently received two additions to its collection of airplane models. Capt. A. Raymond Brooks gave a model of the Ford tri-motored transport which was used as a flying laboratory for many years by the Bell Telephone Laboratories. Sherman M. Fairchild presented a model of the Fairchild PT-19A Army training plane.

Over 700 copies of aeronautical magazines were given for the use of the Institute libraries by Eclipse Aviation Division of Bendix Aviation Corporation.

Robert M. Losey Award to Dr. Horace R. Byers

Dr. Horace R. Byers, Associate Professor at the Meteorological Institute, University of Chicago, received The Robert M. Losey Award for 1941 in recognition of outstanding contributions to the science of meteorology as applied to aeronautics. The award was presented to him by F. W. Reichelderfer, Chief of the U.S. Weather Bureau, at the Honors Night and Tenth Anniversary Dinner of the Institute on January 27.

Dr. Byers joined the staff of the University of Chicago last Fall to assist in the training of Army and Navy officers in meteorology. He is on leave from the U.S. Weather Bureau where he had been engaged in research and the training of personnel since 1935. He has specialized in the air mass analysis method of weather forecasting and was in charge of the section established in the Weather Bureau to introduce this method in its operations.

Dr. Byers was born in Seattle, Washington, March 12, 1906, and was educated at the University of California, where he held the Levi-Straus Scholarship and received an A.B. degree in 1929. He continued his studies at Massachusetts Institute of Technology under Guggenheim and Sloan scholarships and received the degree of Sc.D. in 1935. He served as a research assistant in meteorology at these schools from 1928 to 1933 with the Guggenheim supported Aeronautical Development and Research Foundation at Oakland and at the Scripps Institution of Oceanography, La Jolla, California. From August, 1933, to July, 1935, he was with Transcontinental & Western Air, Inc., instructing airline meteorological personnel and acting as adviser in meteorology to the company.

He has performed original research on Pacific, Alaskan and Canadian weather, charting of upper air conditions, detailed studies of thunderstorms, and the interrelation between precipitation static, icing zones, thunderstorm electricity and the constitution of clouds. He is the author of the book "Synoptic and Aeronautical Meteorology" and numerous technical papers. Both his research work and his considerable experience in training personnel in the latest methods of weather forecasting have been a direct contribution to improved safety and efficiency in aircraft operation.

The Losey Award was presented to Dr. Byers with the citation "For his research in air mass analysis and its applications in synoptic and aeronautical meteorology." He was chosen for this honor by the Committee of Award consisting of Dr. Robert A. Millikan, Chairman of the Executive Council, California Institute of Technology; Dr. Karl T. Compton, President, Massachusetts Institute of Technology; F. W. Reichelderfer, Chief, U.S. Weather Bureau and President last year of the American Meteorological Society; Frank W. Caldwell, President, Institute of the Aeronautical Sciences; and Lester D. Gardner, President, Aeronautical Archives of the Institute. The first recipient of the award, established in 1940, was Henry G. Houghton, Jr., Assistant Professor of Meteorology, Massachusetts Institute of Technology.

The Award was established by the Institute to honor the memory of Captain Robert Moffat Losey, one of its members and a meteorological officer in the Air Corps. He was killed at Dombas, Norway, April 21, 1940, while serving as an official observer for the U.S. Army. He was the first officer in the service of the United States to be killed in World War II.

News of Institute Members

Sidney R. Alexander, Technical Member, is now an Engineer with the Langley Memorial Lab., N.A.C.A. He was formerly an Instructor at the Air Corps Basic Flying School, San Angelo, Texas.

Achille T. Barbero, Technical Member, formerly an Instructor at the Air Corps Technical School, Chanute Field, has joined the Engineering Department of the Grumman Aircraft Engineering Corp.

Martin E. Barzelay, Technical Member, is now an Aeronautical Engineer with the Gould Aviation Div. of the Pratt, Read Co. He was recently associated with the Cluett Aircraft Co.

Ernest L. Bass, A.F.I.Ae.S., formerly Chief Engineer, Aviation Dept., Asiatic Petroleum Co., is now with the Ministry of Aircraft Production, with headquarters at the British Air Commission, Washington, D. C.

William N. Bradley, Technical Member, has left the Consolidated Aircraft Corp. to join the Algoma Plywood & Veneer Co. as Contact Engineer.

Charles H. Christenson, Technical Member, formerly with the Grumman Aircraft Engineering Corp., is now connected with the Bristol Aircraft Div. of Universal Moulded Products Corp.

James M. Coburn, Jr., M.I.Ae.S., formerly Asst. Prof. at the Daniel Guggenheim School of Aeronautics, New York University, is now in the Production Engineering Section, Materiel Div., U.S. Army Air Corps, Wright Field.

Major Joao M. Da Silva, M.I.Ae.S., formerly a Captain in the Brazilian Air Force, is now a Member of the Brazilian Aeronautical Commission.

Col. F. Trubee Davison, M.I.Ae.S., has been named Asst. Chief of Air Staff, A-1, in charge of military and civilian Army Air Forces personnel, it was announced by the War Department. President of the American Museum of Natural History, he has been on active duty with the Army Air Force Combat Command since the summer of 1941.

Floyd J. Fuller, Technical Member, is now an Engineer at the Columbus Plant of the Curtiss-Wright Corp. He was formerly an Engineer with the Douglas Aircraft Co.

Marvin H. Greenwood, Technical Member, formerly a Flying Cadet, U.S. Army Air Corps, has joined the Boeing Aircraft Co. as a Preliminary Design Engineer.

Lt. Daniel Grudin, Technical Member, formerly with the Curtiss-Wright Corp., is now Asst. Engineering Officer, Patterson Field, Fairfield, Ohio.

Pat J. Harney, M.I.Ae.S., formerly a Jr. Meteorologist for the U.S. Weather Bureau at the Mt. Washington Observatory, is now an Asst. Engineer, U.S. Army Signal Corps, Wright Field.

Lt. Comdr. George J. Higgins, U.S.N.R., A.F.I.Ae.S., recently head of the Dept. of Aeronautical Engineering, Univ. of Detroit, is now on active duty stationed at the Post Graduate School, U.S. Naval Academy, Annapolis.

I. Machlin Laddon, F.I.Ae.S., has been named Executive Vice-President and General Manager of Consolidated Aircraft Corp., it was announced by the Board of Directors. Formerly Vice-President and Works Manager, he has been with Consolidated since 1927.

Capt. C. R. de Laubenfels, M.I.Ae.S., formerly in the Design Research Dept. at the Lockheed Aircraft Corp., is now on active duty with the U.S. Army Air Corps as Military Director of the Alighting Gear Unit of the Aircraft Laboratory, Wright Field.

Lt. Harvey A. Leich, Technical Member, is now on active duty with the U.S. Marine Corps, First Marine Aircraft Wing, Quantico, Va. He was recently with the Grumman Aircraft Engineering Corp. as a Jr. Engineer.

Otto H. Lunde, A.F.I.Ae.S., formerly Professor of Aero. Engineering at the Univ. of Alabama, is now a Lt. (jg), U.S.N.R., with the Structures Section, Bureau of Aeronautics, Navy Dept.

Bruno P. Marchi, Technical Member, formerly with the National Aeronautic Association, is now a private in the U.S. Army.

Capt. Henry M. Mullinnix, A.F.I.Ae.S., Naval Aviator, has been promoted to Commander of Patrol Wing Seven, U.S. Atlantic Fleet.

C. N. Paxton, M.I.Ae.S., has left the University of Oklahoma and is now with the Bureau of Aeronautics, Navy Department.

Harry S. Scales, Technical Member, formerly Reserve Meteorologist with T. & W. A., Inc., is now Assistant Meteorologist, Eastern Division, Pan American Airways System.

S. A. Shumovsky, A.F.I.Ae.S., Vice-President of the Central Aero-Hydrodynamic Institute of Moscow, has recently arrived in the United States to serve as an aeronautical specialist on the staff of the Amtorg Trading Corporation. He is assigned to duties at Wright Field in connection with the procurement of aviation equipment under lend-lease arrangements with the U.S.S.R.

John C. Siltanen, Technical Member, is now with the U.S. Army Air Forces.

David G. Stone, Technical Member, has left the Airplane Division (Buffalo Plant), of the Curtiss-Wright Corp., and is a Jr. Aeronautical Engineer at the Langley Memorial Aeronautical Lab., N.A.C.A.

R. Fulton Tangren, Technical Member, is an Aerodynamicist at the Airplane Division (St. Louis Plant) of the Curtiss-Wright Corp.

Harold B. Thayer, Technical Member, formerly Counselor at Boeing School of Aeronautics, is now employed by United Air Lines at San Francisco, Western Division Headquarters, as representative in the Personnel Department.

Harold W. Thomas, Technical Member of the Airplane Division (Buffalo Plant), Curtiss-Wright Corp., has been transferred from Flight Instructor to Test Pilot.

Orville S. Tuttle, Technical Member, has left Lockheed Aircraft Corporation, where he was employed as Senior Design Engineer, to accept the position of Chief Engineer of United States Plywood Corp.

Capt. Walter W. Webster, F.I.Ae.S., formerly stationed in Washington in the Materiel Branch of the Bureau of Aeronautics, Navy Department, is now Manager of the Naval Aircraft Factory in Philadelphia.

Farl O. Weining, M.I.Ae.S., has left the Spartan Aircraft Co., where he was Chief Engineer, and is now associated with the Wichita Division of the Boeing Airplane Company as Project Engineer in charge of their Navy work.

David W. Whittlesey, Technical Member, is now Assistant Mechanical Engineer, Materiel Division, U.S. Army Air Corps, Wright Field.

Sections

Detroit Section. The first meeting of this newly organized Section of the Institute was held on January 7. Officers are: Ralph H. Upson, Chairman; A. M. Kuethe, Secretary; and F. B. Wozniak, Treasurer. Two Curtiss-Wright films were shown, one regarding production of airplanes at the Buffalo plant and the other on engines at the Paterson plant. A technical discussion followed. Meetings are planned to be held on the first Wednesday of each month.

Student Branches

Aeronautical University. The Institute film on "Goodrich De-Icer Development" was shown at a meeting held on December 16. New officers for the 1942 Spring term were elected at the January 20 meeting as follows: Raymond Young, Chairman; Marvin Bley, Vice-Chairman; Robert Beeson, Secretary-Treasurer; and Herbert W. Reed, Honorary Chairman.

University of Alabama. A paper on "The Diesel Engine and Its Development" was presented by Albert Guerney at a recent meeting.

Indiana Technical College. Two slide films, borrowed from the Institute's film library, on "The Engineer's Relation to Production" and "The Engineer's Relation to Assembly" were shown at a meeting held on January 26.

Wayne University. Ralph H. Upson, Chairman of the Detroit Section of the Institute, at a meeting held during the first week in December, spoke on the design, background, and construction of the ZMC-2 all-metal dirigible. Dr. Arthur Carr, Dean of the College of Engineering, who supervised the filling of this dirigible, described the novel method by which this was accomplished.

Personnel Opportunities

The Personnel Bureau serves individual members, as well as organizations seeking to employ aeronautical specialists. Any member or organization may have requirements listed without charge.

Wanted

Experienced layout designer for permanent position with small well-established Eastern Company engaged in Government Contract Work. Address reply to Box 147, Institute of the Aeronautical Sciences.

Available

Aeronautical Engineer with five years aircraft experience of which four and a half have been in the engineering department of a major aircraft company. Holds C.A.A. Ground Instructor, Private Pilot licenses and California State Department of Education teaching credentials for aeronautics. Desires position with school or university offering opportunity to teach aeronautical subjects while obtaining formal education. Address reply to Box 148, Institute of the Aeronautical Sciences.

Chief Engineer of firm designing and manufacturing hydraulic equipment seeks connection. Many years' experience as design engineer on aircraft instruments and accessories. Exceptional organizing and administrative ability. Good leader. Minimum offer acceptable $10,000.00 per annum plus. Address reply to Box 149, Institute of the Aeronautical sciences.